OLUME 102 PART A NUMBER 5 OCTOBER 1955

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

SAVOY PLACE · LONDON W.C.2

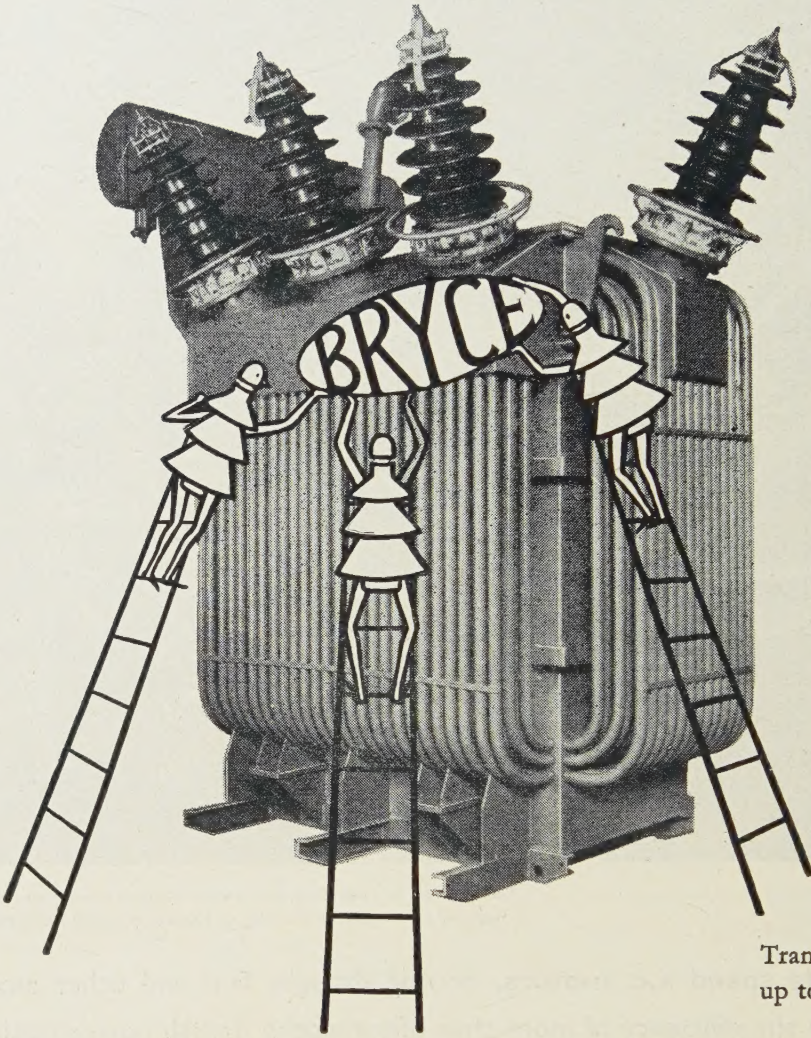
Price Seven Shillings and Sixpence

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871 INCORPORATED BY ROYAL CHARTER 1921

PATRON: HER MAJESTY THE QUEEN

. . . and for TRANSFORMERS the name is BRYCE



Transformers are manufactured up to 15,000 kVA at 132 kV.

BRYCE Transformers are installed throughout the World and are giving unfailing service in climatic conditions as extreme as those of equatorial Africa and Northern Russia.

This dependability is achieved by meticulous attention to detail from design to despatch.

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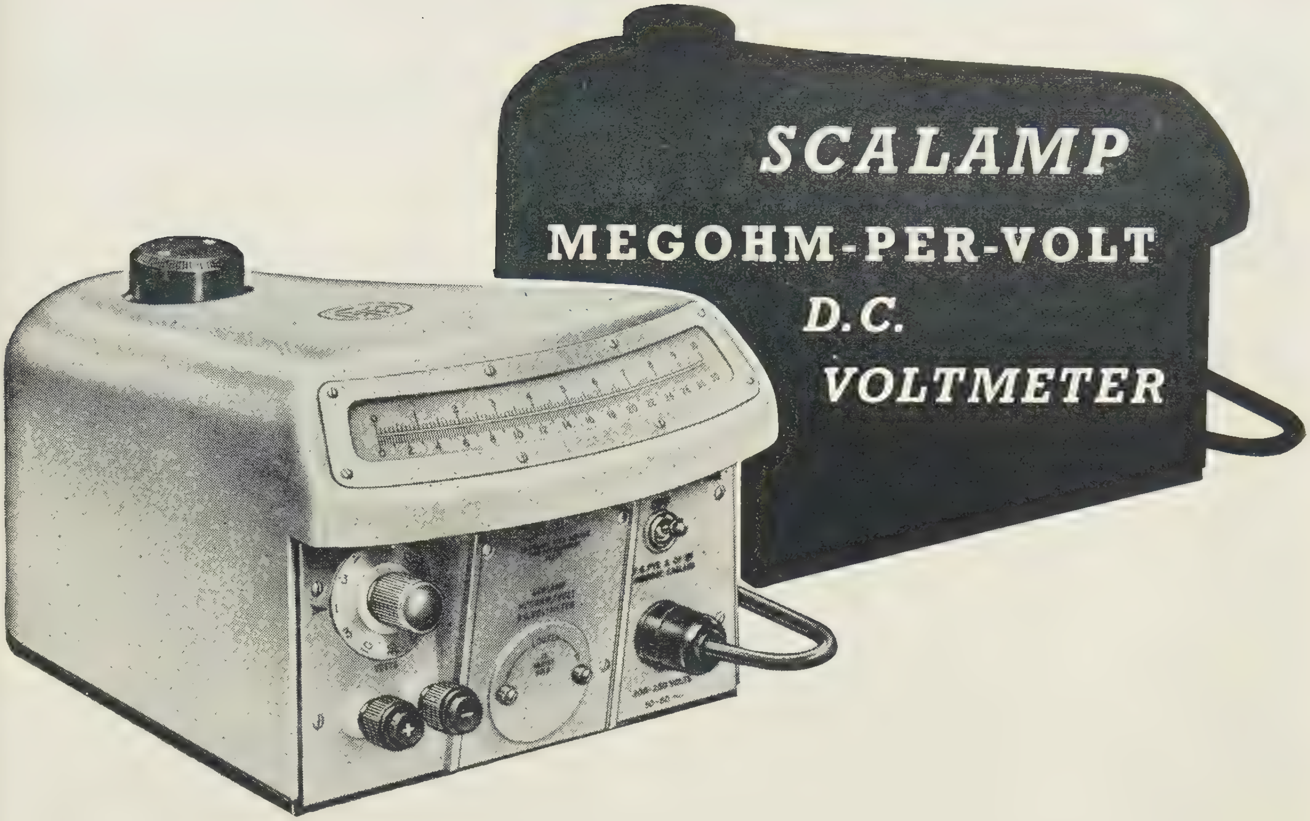
In association with HACKBRIDGE CABLE COMPANY LTD.



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The new Pye "Scalamp" Megohm per Volt D.C. Voltmeter opens up fresh possibilities of measurement in a very wide variety of applications. It is of particular interest to electronic engineers in that it enables measurements of D.C. circuit potentials to be taken directly with higher accuracy than with any comparable instrument. Measurement of insulation resistance can be made with great rapidity and ease. On the upper ranges, the input resistance compares favourably with all but the most elaborate D.C. valve voltmeters, and this without any measurable drift and with complete independence from spurious variations caused by mains or battery supply. The comparative simplicity of construction enables the price to be set at only a fraction of that of instruments of similar performance.

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14 cm ($5\frac{1}{2}$";) scale calibrated in two range 0-10 and 0-30. Ten-way switch giving full-scale ranges of 0.01, 0.03, 0.1, 0.3, 1.0, 3.0, 10, 30, 100 and 300 volts.

Light Spot supply via built-in transformer from 200-250 volts A.C. or from 4-volt battery. Accuracy $\pm 1\%$.

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(*a*) 19 Tubular Copper stranded with 18 Solid Copper.
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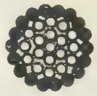

(*b*) 37 Tubular stranded.
1" overall diameter.

(c) 19 Tubular stranded.
0.72" overall diameter.

A section of Bolton's Copper Wire Mill, at Froghall, Nr. Stoke-on-Trent, showing Medium Fine Wire Drawing Machines.

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Established 1783

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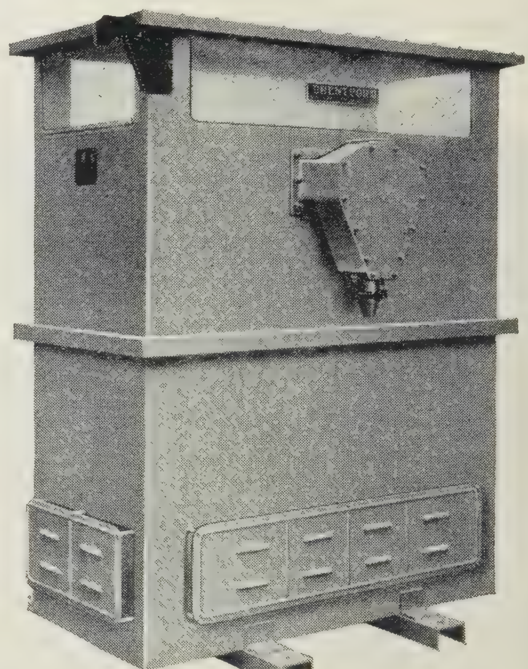

Two types are available in a range of sizes

	kVA.	Voltage
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Class GNH (Sealed in Nitrogen)	Up to 2,000	Up to 15 kV

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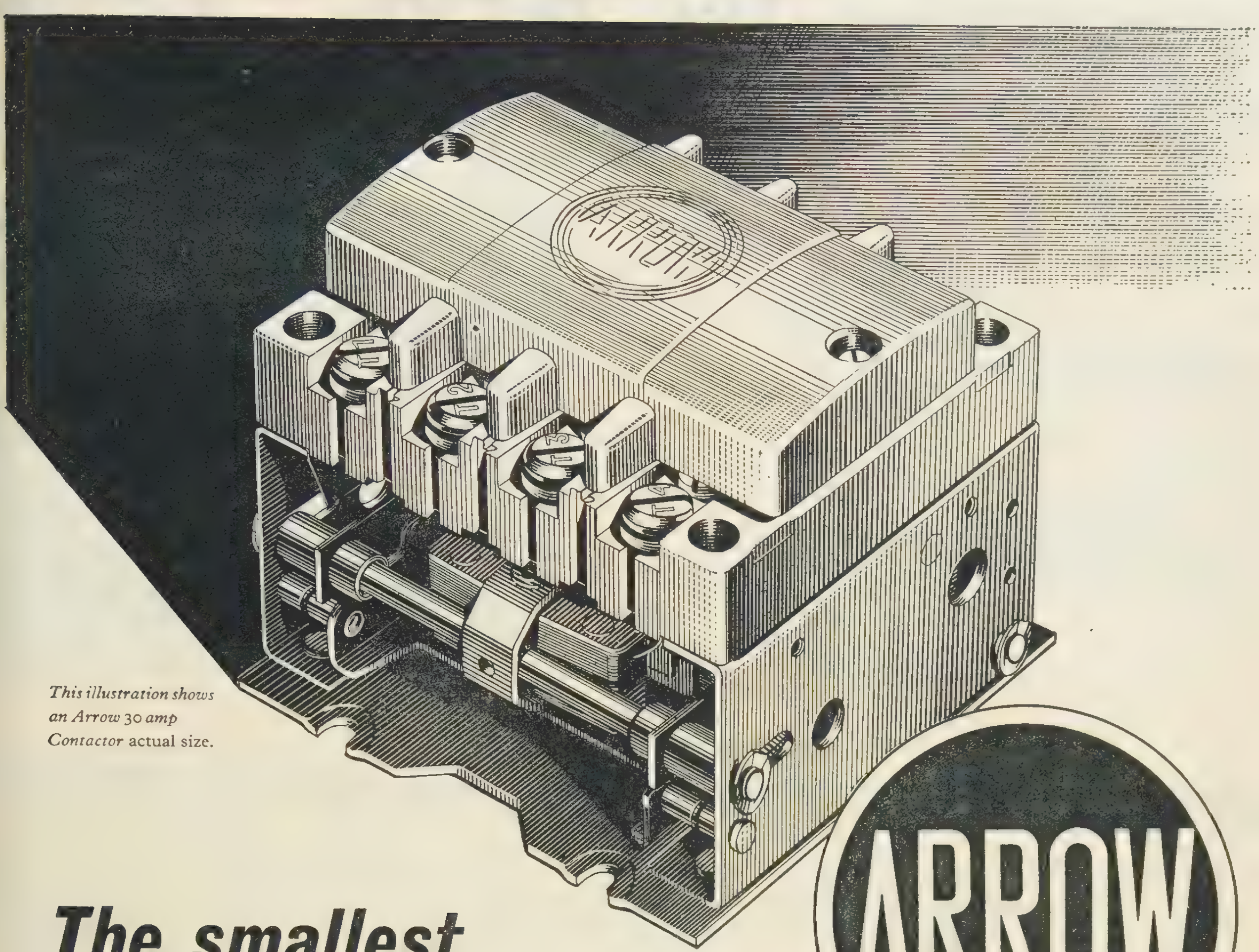

This illustration shows an Arrow 30 amp Contactor actual size.

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Exceptionally low wattage consumption. C.S.A. approved.

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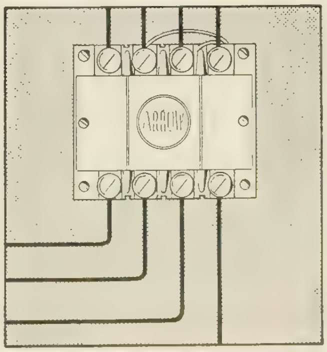

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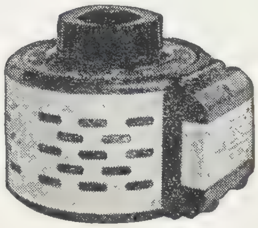

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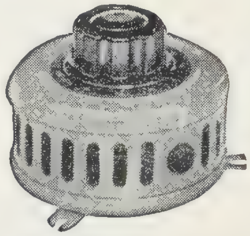

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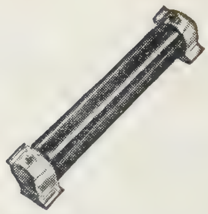

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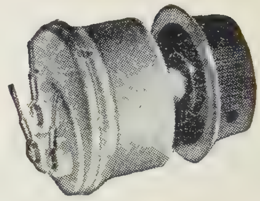
As the result of more than 25 years' hard practical experience in electrical engineering, we are able to offer the widest range of resistors for all purposes.



HERMETICALLY SEALED POTENTIOMETERS

are Type Approved to Class H.1 of RCL 121, 2.5 watt rating for use in Arctic and Tropical conditions. Resistant to damp, heat, cold, fumes, vibration and shock.

★ *Other products from our wide range include*

Protected type shunt field regulators. "REGAVOLT" infinitely variable transformers. Sliding resistances for laboratory use. Range of three moulded knobs with collet fitting for positive grip of circular shafts. Easily fixed and removed. Interchangeable collets for $\frac{1}{4}''$, $\frac{3}{8}''$ and $\frac{5}{16}''$ shafts.

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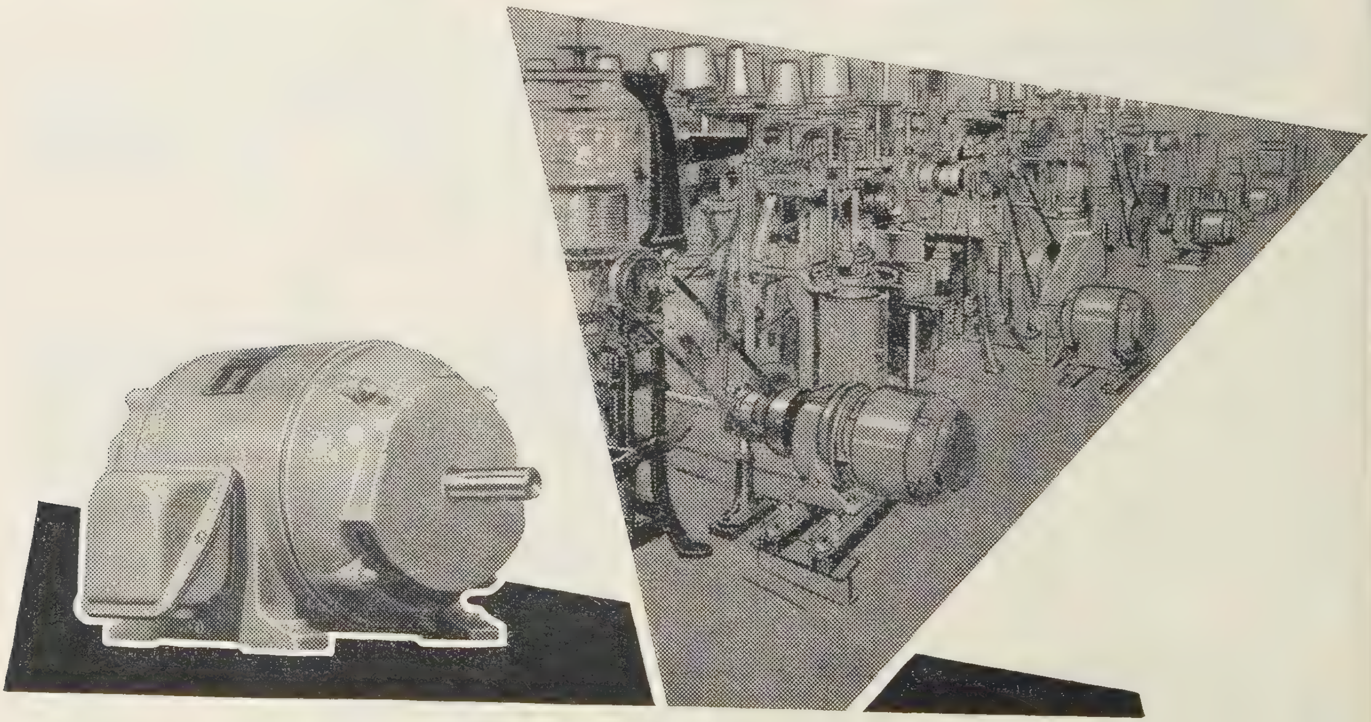

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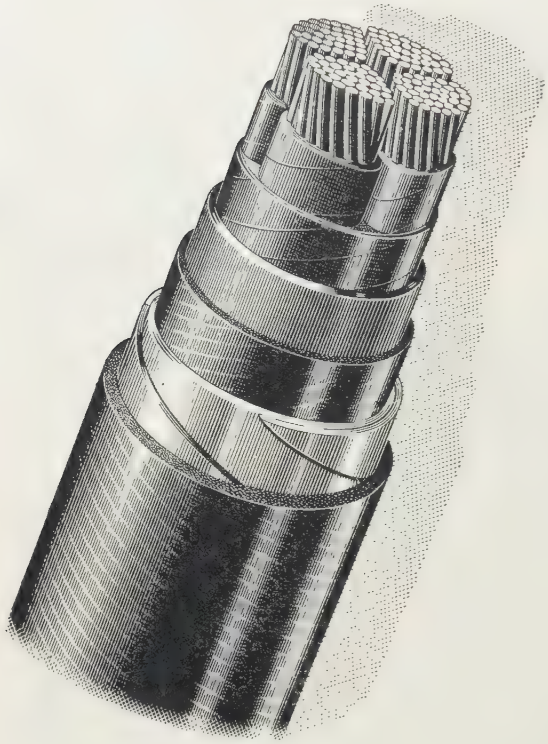

Many cables are made to specification but it is by their attention to the unspecified *details that Aberdare's reputation has been built.*

Aberdare Cables

Paper insulated cables up to 33kV, to BSS or special requirements.

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Recent developments of Thyratron technique have made it possible to produce a compact and portable instrument so that the peak voltages can readily be determined either in the laboratory or in the field.

The Varley Peak Volt Meter fills this need and is an essential piece of equipment for any electrical laboratory or test department. It is one of the very few instruments of its kind on the market, measuring transient voltages from 5 to 35,000 volts to an accuracy of approximately 10%.

PRICE £35 NET

The Specialists in Electro-Magnets

We also supply Transformers, Solenoids, Relays, Mercury Switches, Permanent Magnets and Heating Equipment.

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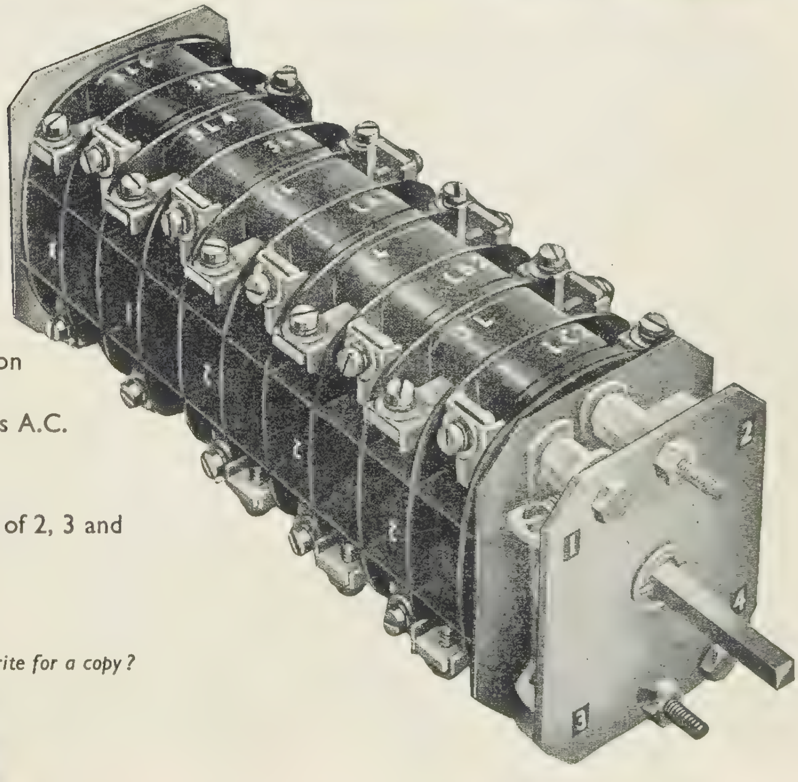
consider these points



★ Self-cleaning silver-to-silver contacts.

★ Generous clearance and creepages.

★ Easy-to-wire terminals.

★ High make and break capacities.

★ Cam-operated, spring-loaded, four position mechanism.

★ Two sizes: 30 amps and 60 amps 550 volts A.C. and D.C. Two to five poles.

And these typical applications:—

★ Forward and reverse control and control of 2, 3 and 4-speed change-pole motors.

And add:—

★ Robust and compact construction.

Leaflet 2017 gives the full specification. Why not write for a copy?

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A Metal Industries Group Company.

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FOR ACCURATE AND AUTOMATIC PROCESS CONTROL

★ Scale ranges from 0-10 secs. up to 24 hours.
★ Settings down to 1/10 sec.
★ Accuracy within 0·25% of full scale range.
★ Available as single units for self-mounting or as complete control panels.
★ Any operation requiring time control by electrical means can be regulated by this instrument.

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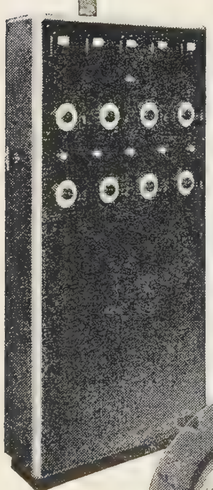

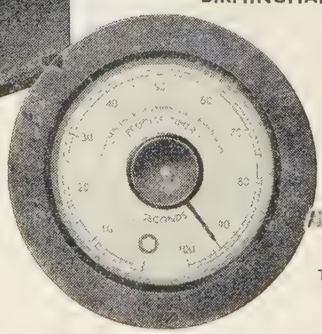

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ELIMINATE COMPOUND DRAINAGE . . .

. . . . by using GLOVERS STANDARD PAPER INSULATED CABLES . . . . which are NON-DRAINING in any situation

GLOVERS STANDARD CABLES "for normal distribution work can be used for vertical installation without any special precautions being necessary . . ."

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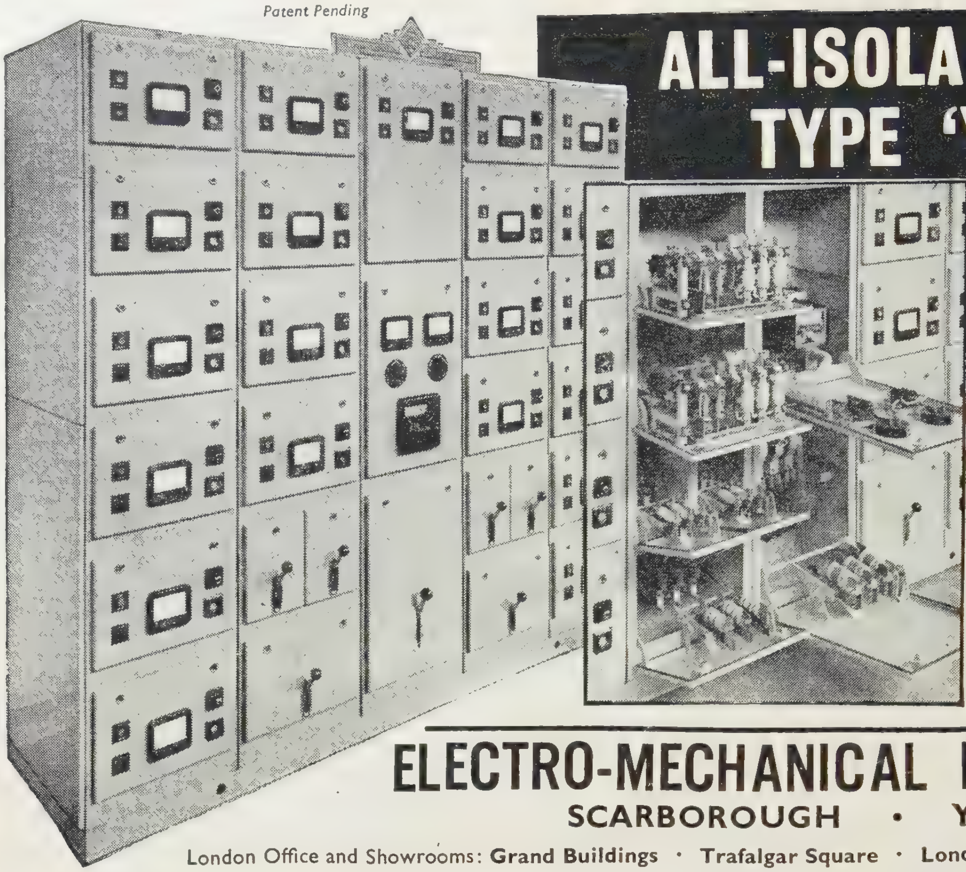

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- Complete accessibility to all Starters and Fused Switches.
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- For Indoor or Outdoor use in any climate.

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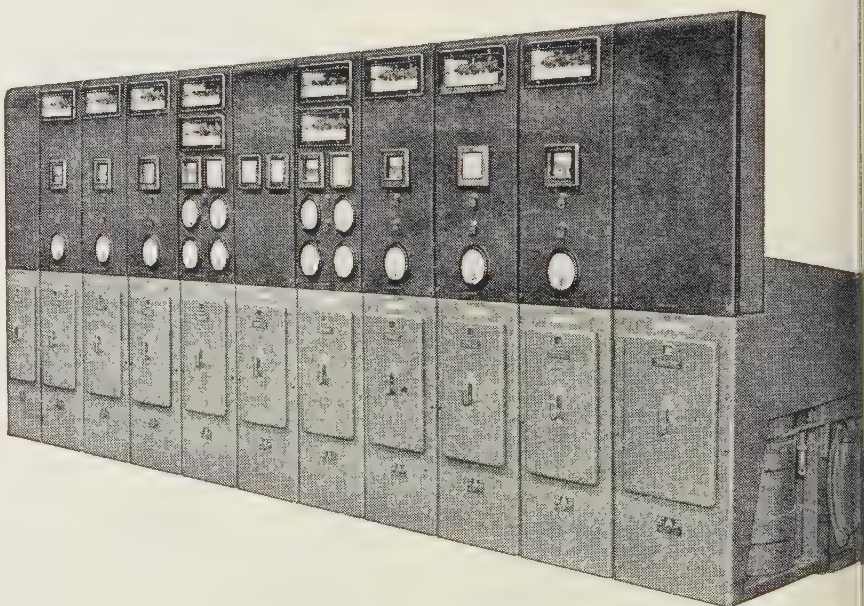
Typical 11 kV 250 MVA IVI switchboard embodying arc trapped circuit breakers for important industrial sub-station.



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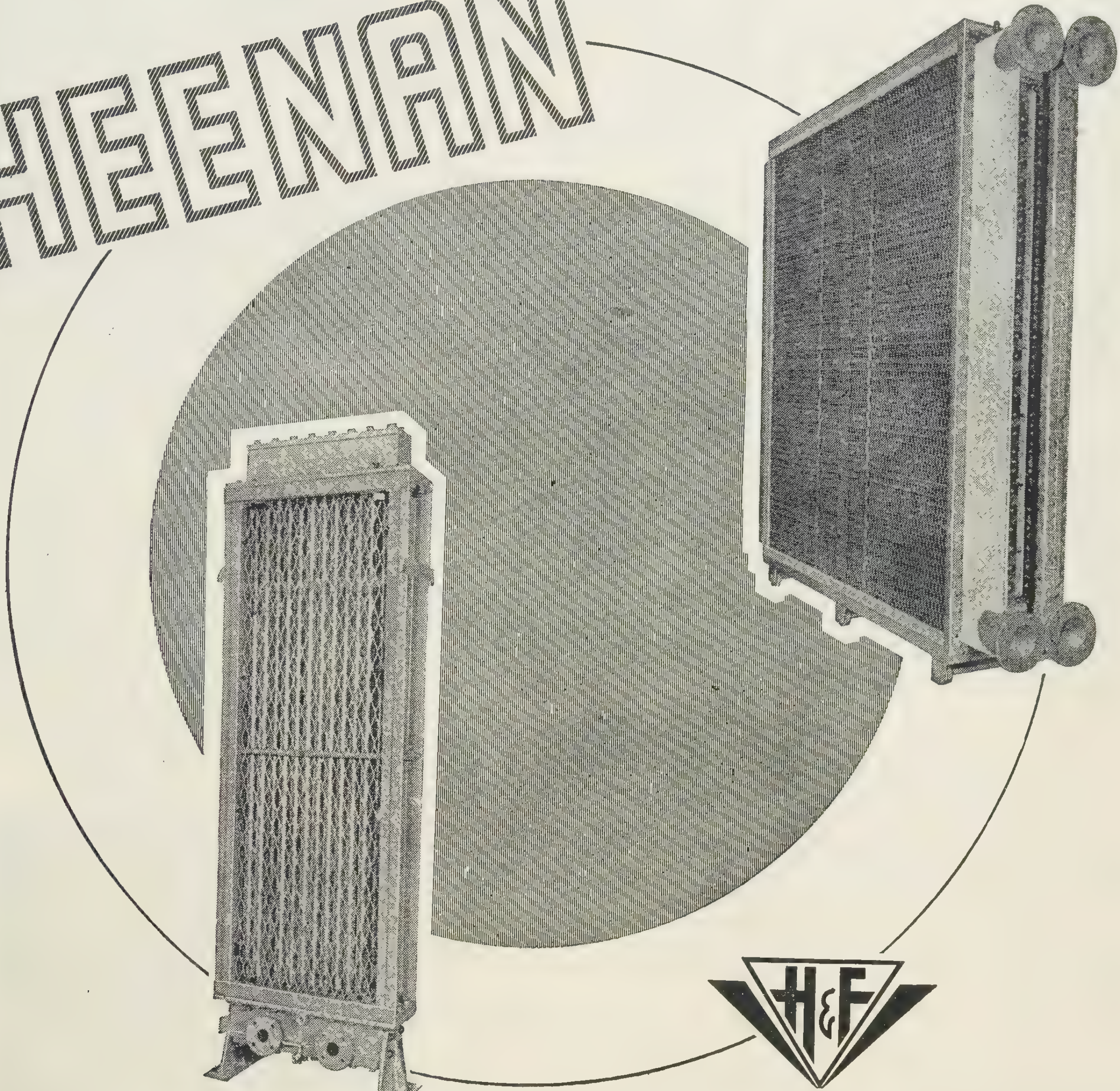

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AIR COOLERS

Lengthy experience in practical design
Wide variety of ducting and damper layouts
Highly efficient cooling surfaces
Heavy and robust construction
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(The names 'Heenan' and 'Froude' are registered trade marks of the Company)

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High efficiency electro-precipitation

by ***Simon-Carves Ltd*** SIMON ENGINEERING GROUP

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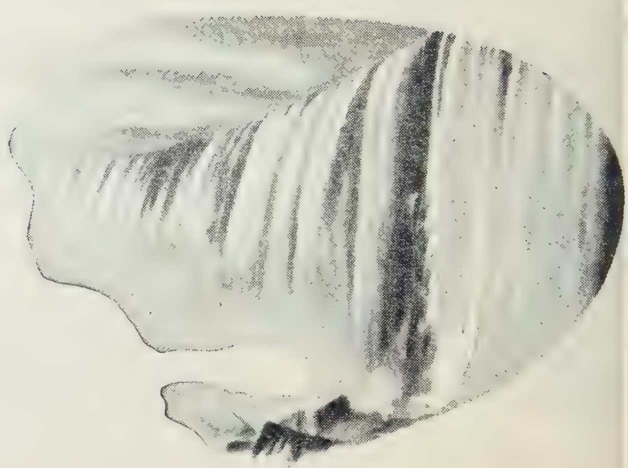

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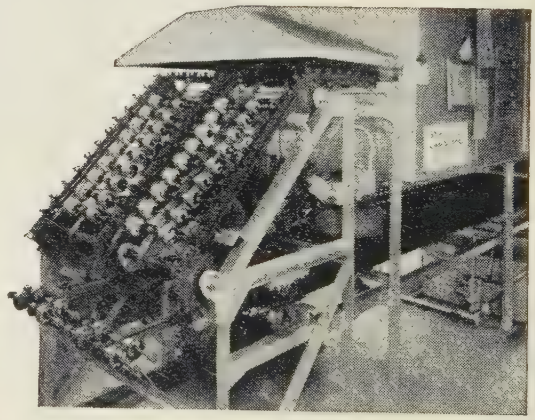

In this Plant for Messrs. Hoover Ltd., 275 vacuum cleaner armatures per hour are impregnated with insulating varnish by the revolutionary patented Zanderoll Process.

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dm ST

G.E.C. Remote Supervisory Control for British Railways, Southern Region

(ABOVE) *Inside the Raynes Park control room. From here 527 switches will be remotely operated and 627 indications will be received. The wall diagram is 29½ feet long.*

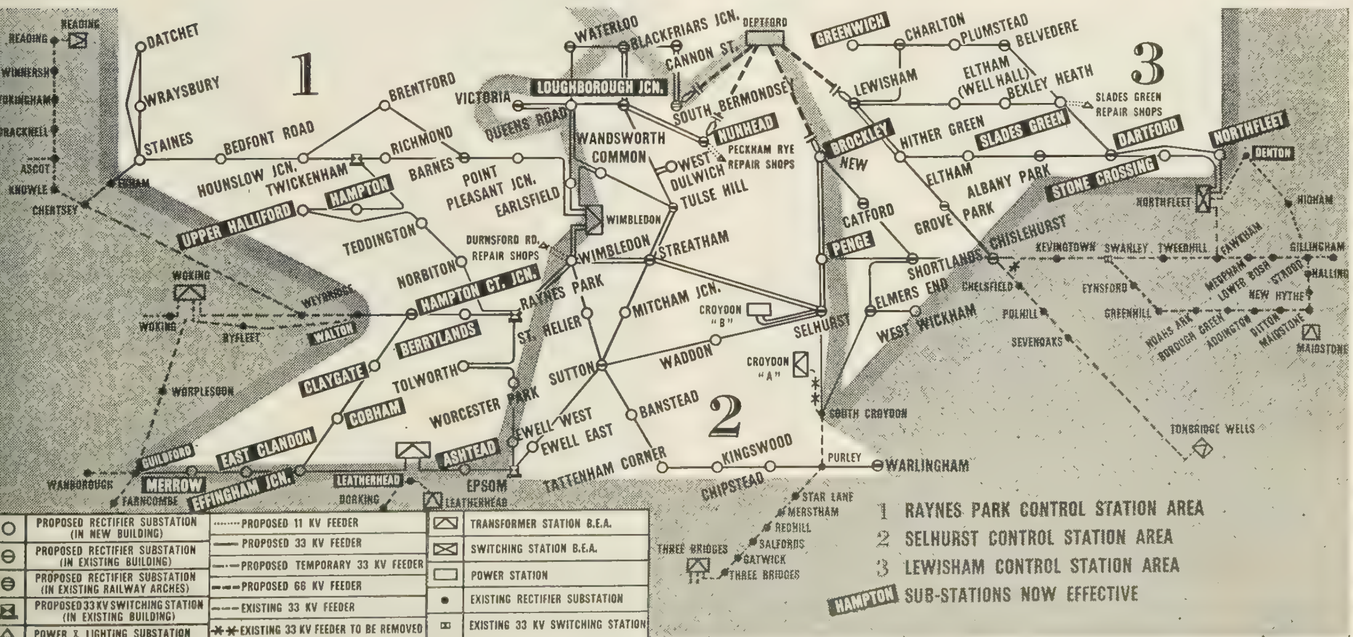
Considerable progress has been made with the Southern Region's extensive power-standardisation programme.

The control system is already in part commission on the Region's Western, Eastern and Central Section (see map below). Each section has its own Control Room and altogether 71 rectifier substations and 70 track paralleling huts will be needed.

Approximately 1,500 circuit breakers will be connected to control and/or indicating equipment.

The high-tension switchgear for the Western and Central Sections of the scheme has been supplied by The General Electric Co., Ltd. They have also supplied all the rectifiers for the Central Section.

When the scheme is completed, British Railways will have taken a big step towards greater efficiency, leading to an improvement in their already impressive record for safety and punctuality in this Region.



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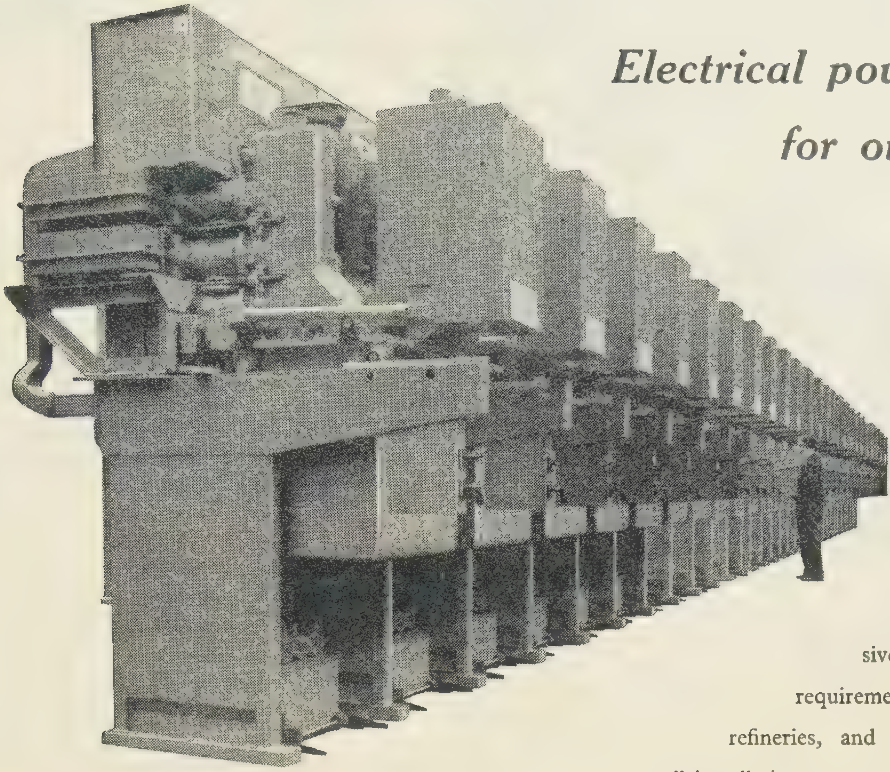

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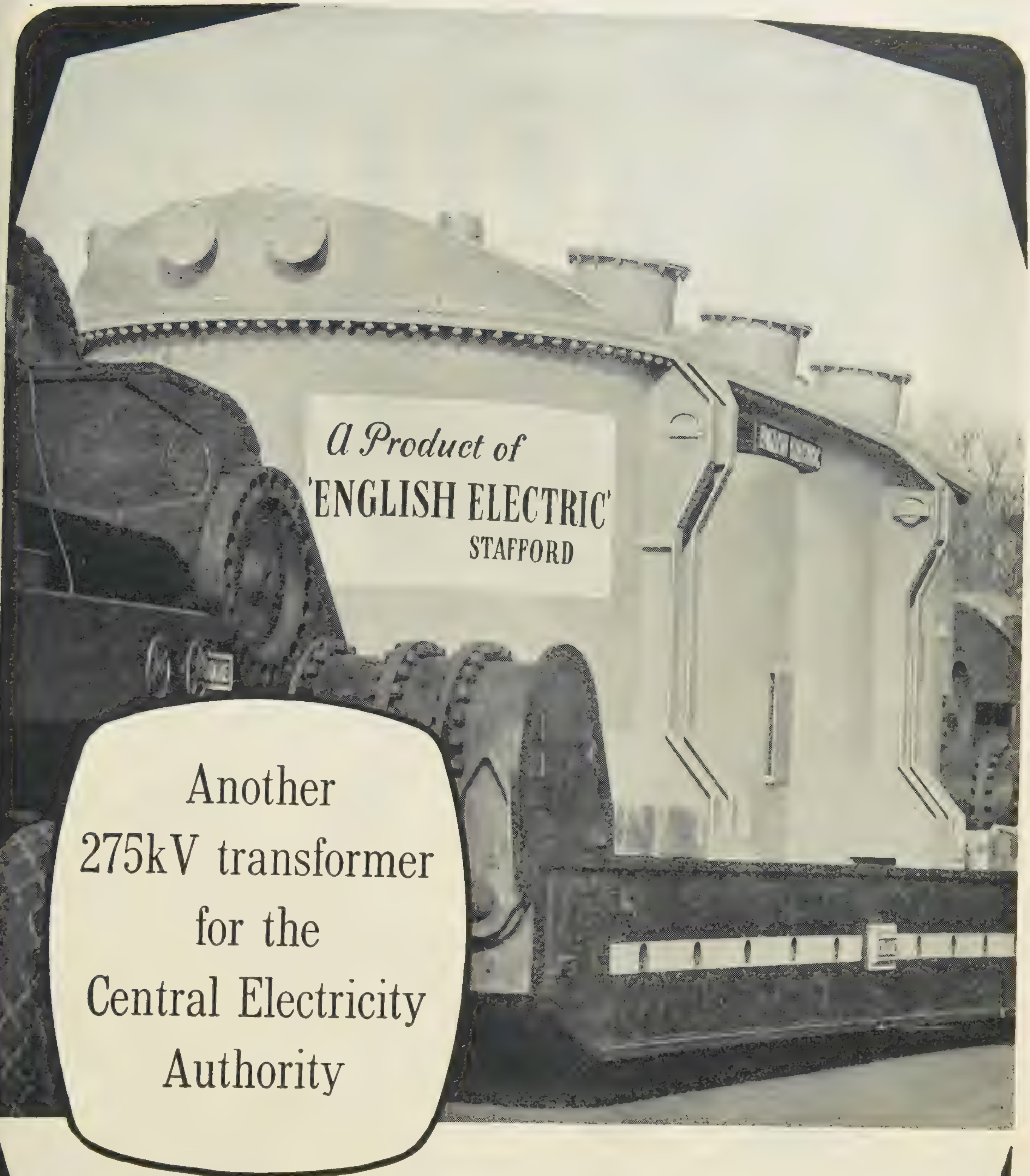
THE PROCEEDINGS OF THE
INSTITUTION OF ELECTRICAL ENGINEERS

TEN YEAR INDEX
1942—1951

A TEN-YEAR INDEX to the *Journal of The Institution of Electrical Engineers* for the years 1942–48 and the *Proceedings* 1949–51 (vol. 89–98) can be obtained on application to the Secretary.

The published price is £1 5s. 0d. (post free), but any member of The Institution may have a copy at the reduced price of £1 (post free).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Our wide experience in the field of automatic control has long been recognised by designers and users of production plant.

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VOL. 102. PART A. No. 5. OCTOBER 1955

21.357.8

Paper No. 1866 U
Oct. 1955

ELECTROLYTIC PROCESSES FOR SURFACE CONDITIONING OF METALS

By Professor J. W. CUTHBERTSON, D.Sc., Associate Member.

(*The paper was first received* 12*th April*, 1954, *and in revised form* 21*st March*, 1955.)

SUMMARY

The uses of electrolysis, for the surface cleaning and descaling of metals, for improving the resistance of aluminium and its alloys to oxidation and abrasion, and for the polishing of metals, are discussed.

Compared with direct-immersion processes, electrolytic cleaning and descaling is often speedier, more efficient and easier to control. In cathodic cleaning, adventitious matter is loosened by the nascent hydrogen evolved on the surface of the work, while the gas itself is a powerful reducing agent. Anodic pickling in acid electrolytes is precise in action and avoids the dangers of hydrogen embrittlement and of over-pickling. Alternate anodic and cathodic procedures offer certain advantages that are leading to their wider adoption.

Theory and practice in the anodic oxidation of aluminium are discussed; reference is made to the use of this type of process to facilitate photographic reproduction on the surface of the metal, and to modifications of anodizing technique designed to produce especially hard, wear-resisting films.

The principles of electrolytic polishing are explained. Industrial practice in the electrolytic polishing of steel, nickel, copper and aluminium is outlined. A comparison is drawn between electrolytic and mechanical polishing, and some reference is made to the economics of the electrolytic process.

(1) INTRODUCTION

Electrolysis features largely in the surface preparation of metals and alloys. At the beginning of this century almost the only use of electrolysis was for the extraction of metals and for electroplating. To-day the field is much wider and electrolytic processes are now used extensively by many branches of industry for cleaning and descaling metals and for producing surface finishes that either cannot be obtained, or can only be obtained less cheaply, by alternative procedures. These latter applications include, in particular, the anodic oxidation of aluminium and the electro-polishing of metals. The demand for increased production has stimulated interest in these processes, and their development has proceeded rapidly in recent years. Electropolishing is a comparatively new process but has already made substantial headway. Developments in cleaning procedures have been mainly along the lines of expansion of use and improvement in technique; the simple cathodic and anodic processes have been replaced by combined cathodic-anodic procedures in certain large-scale applications, as is described in the sequel. The anodic process for the oxidation of aluminium has not altered fundamentally since it was introduced some thirty years ago, but noteworthy advances have been made in adapting the process to produce especially hard coatings for engineering applications.

(2) ELECTROLYTIC PROCESSES FOR THE CLEANING AND DESCALING OF METALS

Electrolytic processes play an important part in the surface preparation of metals. While solvent degreasing and acid pickling are accepted practices for treating the bulk of work that has to be freed from grease and scale respectively, these processes are often supplemented and sometimes replaced by electrolytic procedures whose advantages make them attractive under suitable conditions. Speaking generally, the conversion of a cleaning or descaling process from a simple chemical procedure to an electrochemical one improves the efficiency of the process, increases its versatility, increases its speed of operation, and possibly reduces metal losses. Electrolytic treatment may be purely cathodic, purely anodic or a combination of both. Cleaning is usually, but not invariably, done in alkaline solutions. Acid solutions are favoured for descaling and for etching. There are no firm rules governing procedure and the type of electrolyte, and many different systems have been devised. A few procedures have become more or less standardized, and only these will be dealt with in this report.

(2.1) Cathodic Processes

Electrolytic cleaning in alkaline solutions is almost universal practice in the preparation of work for electroplating and is widely used for other purposes. In this process the work is made the cathode in a hot solution containing, for instance, trisodium phosphate and sodium metasilicate; the composition and concentration of the electrolyte are not of fundamental importance so long as the solution is alkaline and has a reasonably high electrical conductivity. The electrolyte is non-corrosive and may therefore be contained in an unlined steel tank. The tank may be used as the anode, but closer control over the cleaning is possible if separate anodes of steel, or

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Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
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preferably of nickel, are used. The voltage across the tank is in the range 6–15; the current density may be as high as 100 amp/ft^2, but in practice more attention is paid to voltage than to current density. All that is required is that the current density shall be high enough to cause hydrogen to be copiously liberated over the surface of the work, and the experienced operator has no difficulty in satisfying this requirement by adjustment of the voltage. Hydrogen is liberated in stoichiometric yield at the cathode, and the cleaning action is primarily due to the disruptive effect of the gas bubbles, which loosens and detaches foreign matter, leaving the alkaline solution free to complete the cleaning of the surface.

The electrolytes used in alkaline cathodic cleaning are usually dilute. Their electrical conductivity increases quite rapidly with temperature, and it is customary, in the interests of economy and efficiency, to operate this type of process at a temperature approaching boiling point. This method of cleaning is cheap and, compared with cleaning in alkali without current, is more effective. Most forms of surface contaminant, including saponifiable and non-saponifiable matter, yield to the electrolytic process, but work that is heavily contaminated with oil or grease should first be subjected to solvent degreasing; otherwise the oily matter will soon clog the electrolyte.

The process is applicable to practically all metals and alloys. It has few disadvantages but should be used with caution for the cleaning of steel, especially high-carbon steel, if hydrogen adsorption cannot be tolerated. With spring steels, in particular, the danger of hydrogen embrittlement is considerable, and although it is often claimed that the hydrogen can be removed, and along with it the brittleness, by subsequent low-temperature heat treatment, the complete removal of the adsorbed gas is not always so simply effected. Anodic processes are the only safe electrolytic procedures to adopt in such cases. Another, but less serious, objection to cathodic cleaning is the tendency for metallic impurities present in the electrolyte to deposit on the surface of the work if their deposition potentials are favourable. Copper will always deposit in this way. It is fairly easy in practice to keep the concentrations of dissolved metallic impurities to a low value, and if trouble is still experienced any metallic film that forms on the work can be stripped off by reversing the current for a few seconds towards the end of the period of treatment.

Several variations of this process exist. Combined cathodic cleaning and flash copper-plating from an alkaline solution containing sodium cyanide and a little copper cyanide used to be practised fairly widely in the plating trade. This process appealed because the deposition of the copper on the work was deemed to be a visual indication of efficient cleaning. Such is not always the case, however, and this uncertainty, coupled with the objections on toxicity grounds to the use of a cyanide-containing solution in a process which evolves large quantities of gas, and hence of spray, has led to a decline in the popularity of this cleaning procedure.

Cathodic treatment in acid electrolytes is becoming increasingly popular for pickling steel when the degree of scaling or oxidation is relatively mild. An example of this type of process is for the pickling of tinplate steel for hot-dip tinning. A diagrammatic view of a typical cleaning unit is shown in Fig. 1. The electrolyte in this case is dilute hydrochloric acid; the anodes are of carbon. The current consumption for such a unit is about 500 amp at 6 volts.[1]

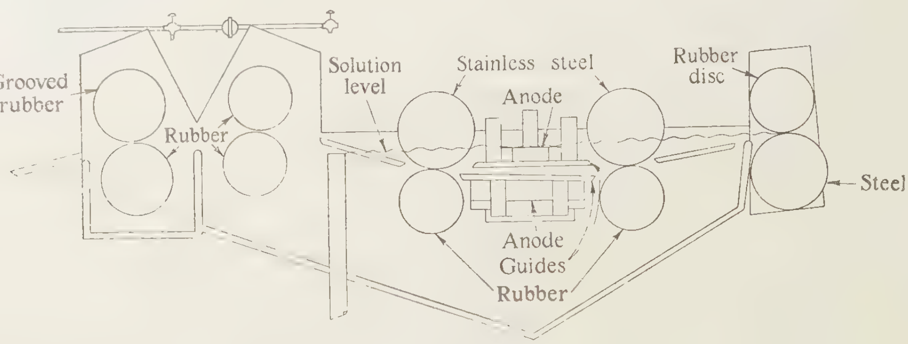

Fig. 1.—Cathodic pickler, as used in the preparation of steel sheet for hot-dip tinning.

Another cathodic process in which an acid electrolyte is employed, the Bullard–Dunn process,[2] is really a combined descaling and cleaning procedure. This process is intended for the removal of scale or oxide from iron and steel by acid attack assisted by cathodically liberated hydrogen. The electrolyte is hot dilute sulphuric acid and contains 1 g per litre of stannous sulphate. The work is treated cathodically at a current density of 60–80 amp/ft^2. The anodes are insoluble high-silicon iron but a few tin anodes are included to replenish the tin content of the electrolyte. As the scale is removed, tin deposits and affords protection to the underlying cleaned metal. Owing to the high hydrogen over-voltage of tin as compared with iron oxide, there is a tendency for hydrogen liberation to be diverted away from the tin-coated areas and at the same time the current density on the areas still covered with scale increases. There is thus an acceleration in the rate of pickling as descaling proceeds. Ultimately, even the most inaccessible areas are effectively descaled. The complete removal of scale from such areas by pickling in acid without current could be effected as expeditiously only at the expense of considerably greater attack on the more readily accessible areas. If, after descaling, the tin coating on the work is not wanted the tin is stripped off anodically and is recovered. For some purposes the presence of the tin is an advantage; underneath paint it increases corrosion resistance while it facilitates such further operations as hot tinning and the casting-on of bearing alloys.

Scale can be very effectively removed from steel by cathodic treatment in molten sodium hydroxide. A process of this type has been used for the preparation of steel wire for continuous electrogalvanizing. The procedure is not without hazard, however, especially if it is operated on a large scale, and there has been a tendency to abandon it in favour of anodic pickling in acid.

(2.2) Anodic Processes

Anodic treatment in sulphuric acid is used for pickling and etching steel. Compared with chemical pickling in acid, the

nodic process is faster and can be operated at a much lower emperature. Moreover, the anodic polarization tends to make he steel passive, and consequently as descaling approaches ompletion the rate of attack on the metal underneath diminishes. 'ull passivity is not likely to be developed in dilute acid, such s is used in standard pickling practice, but, nevertheless, the pplication of current reduces attack on the basis metal and nsures that the attack is more uniform than in non-electrolytic ickling.

Anodic treatment in 8–10% sulphuric acid at 50–100 amp/ft^2 used for pickling and etching tinplate steel. The electrolyte not heated and usually operates at about 25°C. Another pplication of this process is for the preparation of steel wire or electrogalvanizing. The procedure adopted in one British lant has been described by Roebuck and Brierley[3] and involves eatment of the moving wire at a minimum anode current ensity of 500 amp/ft^2 in a solution containing 240–260 g per tre of sulphuric acid and 50–80 g per litre of zinc, the temerature being not above 32°C. Lead-1% silver-alloy cathodes re used, and contact with the wire is made through a roller of luminium-12% silicon alloy. The cells are 9 ft long and are onstructed of mild-steel lined with lead.

Anodic treatment in more concentrated sulphuric acid is mployed for etching steel to promote good adhesion of electroeposits. In this process the acid is used cold and the appliation of current leads first to some dissolution and later to the evelopment of passivity. A solution of acid concentration 30% y volume is commonly used for other than work that already as a bright finish. The application of about 6 volts across the ank will cause a current of 100–200 amp to flow, and with acid f this strength the current does not greatly diminish with time. During the first few seconds oxide and any surface contaminants re removed, while some metal is actually dissolved. Thereafter the rate of dissolution falls off rapidly and the metal tends become passive and to function as an oxygen electrode; here is thus copious gas evolution from its surface, and this ay make the process unattractive for treating tubes or similar rticles where there is danger of the electrolyte being blown ut of the bores by the pressure of accumulated gas. The rocess only takes a minute or two, after which the metal has a atin-like etched finish that is very suitable for the reception of ectro-deposits. Polished work cannot be treated by this rocess, as the etching it produces is sufficiently severe to destroy e polish. If the strength of the acid is increased to about 38% y volume, the conductivity of the electrolyte is lowered and the itial current density for the same applied voltage is much duced. Passivity develops very rapidly, and the current multaneously diminishes towards zero. Attack on the basis etal is lessened, and the finish obtained is, in fact, more akin that resulting from electro-polishing than from etching.

(2.3) Cathodic–Anodic Processes

Reversal of polarity at intervals during cleaning in alkali is ommonly used in the preparation of work for plating. This rocedure keeps the work free from metallic films, tends to duce hydrogen embrittlement, and sometimes exercises a eneficial pickling effect. Processes of this type have been eveloped on a very large scale for the cleaning of steel strip in onnection with the production of electrolytic tinplate.

The electro-tinplate process was introduced in the United ates shortly before the outbreak of the last war. The process as since grown to the extent that more than half the tinplate ow produced in America is made in this way. There are now existence over the world 41 electro-tinning lines having a ted production capacity of nearly 5 000 000 tons per annum.[4] the development of this industry many problems not previously encountered in electro-deposition practice had to be solved, not the least of these being the cleaning and pickling of steel strip moving at very high speeds. Cleaning is necessary at two stages of the process: (*a*) after cold reduction of the steel prior to annealing, and (*b*) after the final temper-rolling prior to pickling and plating. When it is realized that the speed of travel of the strip may be as high as 2 500 ft/min as it passes through the plating unit, the formidable nature of these cleaning problems will be appreciated. In both of the above stages of the process, cleaning is necessary to remove rolling lubricant. In the latest practice the favoured procedure is alternate cathodic and anodic treatment of the strip as it passes through an alkaline solution. The cleaning units may be up to 50 ft in length, while the current requirements may run into thousands of amperes. At the Trostre works of the Steel Company of Wales, 12 000 amp is available for preparation (including anodic pickling) in each of two Ferrostan (stannous sulphate–phenolsulphonic acid) electrotinning lines, while the No. 4 line of the Weirton Steel Co. in the United States has about 40 000 amp on tap for the same purposes.[4] It is noteworthy that all the low-voltage d.c. requirements of the Trostre lines are supplied by selenium rectifiers. Where such heavy currents are involved, reversal of polarity by switching is impracticable and the strip is therefore made alternately anodic and cathodic by causing it to pass in its travel between pairs of insoluble electrodes, one on either side, which themselves are connected alternately to positive and negative supply lines. In the cleaners installed at Trostre for removing oil from the steel prior to annealing, the strip passes horizontally through the cells and the electrodes are grouped above and below it. The speed of the strip through these cleaners can reach 2 000 ft/min.[5] A typical cleaning unit may contain four sets of grids in two electrical groupings, each of which comprises one positive and one negative set of grids fed by a 16-volt generator delivering 3 000 amp.[6] A favoured arrangement for cleaning the strip before it enters the pickling and plating cells is to pass it through the cleaning cell vertically in a serpentine manner, over top and bottom rollers. The vertical sections of the loops are made alternately anodic and cathodic. The solutions used in these cleaning processes are specially compounded for the purpose. The Ferrostan electro-tinning process favours a mixture of sodium hydroxide and trisodium phosphate in water used at a concentration of a few pounds per 100 gal and maintained at a temperature of 95°C.[7]

Alternate anodic and cathodic treatment is not confined to alkaline cleaning. Variation of the polarity in the pickling of tinplate steel in warm dilute sulphuric acid is now being adopted in some plants with apparently good results. The current density ranges between 100 and 400 amp/ft^2; in one instance the strip is made cathodic-anodic–anodic-cathodic in four stages.

(3) ANODIC OXIDATION OF ALUMINIUM

The metal aluminium occupies a strongly negative position in the electrochemical series. Theoretically, aluminium should displace hydrogen from water, and the fact that it does not normally do so is partly explained by the ease with which the metal forms a protective surface film of oxide.

While the naturally formed oxide film gives some measure of protection against corrosion, it is not sufficiently protective to satisfy many practical applications of the metal. Moreover, the natural film is thin and relatively soft, and consequently it can easily be damaged. Many years ago it was shown that an oxide film of superior protective properties could be produced on aluminium by treating the metal anodically in a suitable electrolyte. It was found that the properties of the film could in some cases be improved by subjecting it to a sealing treatment,

while the discovery that the film could be dyed, thus providing a ready means of colouring aluminium, was an added attraction. The so-called anodic oxidation process for the treatment of aluminium alloys made rapid progress, and to-day the procedure, in one form or another, is employed widely wherever there is a demand for protecting, for decorating, and for increasing the wear resistance of these materials.

Of the common metals, aluminium is unique in lending itself to useful anodic oxidation. Many attempts to devise a similar process for the treatment of magnesium have been made, but although it is possible to produce an anodic coating on that metal, the degree of protection that the coating affords is far below that obtainable when aluminium is similarly treated. Differences in the physical characteristics of the oxide films obtained in the two cases may explain the inferior results obtained with magnesium.

(3.1) Theoretical Considerations

Much has been written on the theory of the anodic oxidation of aluminium, and there has been some conflict of ideas regarding the mechanism of the process. Whatever mechanism is accepted, it is apparent that during the actual treatment the growing oxide film must be sufficiently pervious to allow the oxidant to penetrate it and to react with the metal underneath. The growth of the oxide film can only occur at the oxide-metal interface; the film is produced by reaction between the basis metal and an oxidizing reactant which could be either oxygen or the hydroxyl ion. Studies of the growth of the oxide film have indicated that the mode of formation of the anodic layer is complex and occurs in at least two stages. The first stage appears to be the formation of an active layer of hydrated aluminium oxide on the surface of the metal. As oxidation proceeds, the oxide film grows from the active layer, which is continuously sustained by reaction at the surface of the metal, without itself suffering appreciable change in thickness or in electrical properties. It has been suggested that, under a sufficiently high potential gradient, alumina is transported from the active layer to the growing layer by a process of dehydration of the active layer.[8] Growth proceeds continuously or intermittently, according to whether the current flowing is unidirectional or alternating, but not necessarily at a steady rate.

Measurements of change in the capacitance and resistance of aluminium electrodes during anodic oxidation in acid electrolytes using alternating current have indicated that while the resistance increases with time the capacitance remains fairly constant.[9] It is thus inferred that the active layer is the seat of the capacitance effect; both layers contribute to the resistance, and for thin films the contribution of the active layer to the overall resistance is considerable.

In all anodizing processes concomitantly with the formation of the oxide film there is some dissolution of the film by direct chemical reaction with the electrolyte. The amount of metal lost in this way varies considerably with the nature of the electrolyte employed, with the operating conditions, and with the composition of the basis metal in the cases of alloys. Bradshaw and Clarke,[10] referring to the anodizing of aluminium and aluminium alloys in 20% sulphuric acid at a constant potential difference of 11–12 volts, find that the percentage of the total current corresponding to the weight of alumina obtained at the anode varies from 28% for aluminium-10% copper to 66% for aluminium-7% magnesium, the figure for aluminium itself being 51%. This solvent action of the electrolyte has an important effect on the structure of the anodic film, as it is responsible for the porosity which is a characteristic feature of these films. The greater the solvent action, the greater the porosity, and hence sulphuric acid produces much more porous films than does chromic acid. The pores in the coating appear, not to extend completely down to the parent metal, but to terminate at the barrier or active layer. In sulphuric-acid anodizing it has been calculated that the pores have an average diameter of 107 Å, and that there are $1 \cdot 55 \times 10^{11}$ pores per cm^2 of surface. Spooner[12] has pointed out that owing to the large *IR* drop across the barrier layer at the bottom of the pores, the temperature of the electrolyte within the pores is likely to be markedly higher than that of the bulk of the solution, and because the solvent action increases as the electrolyte becomes hotter, he suggests that this factor may be mainly responsible for the formation and growth of the individual pores. This reasoning is consistent with his observations on the effect of air agitation on the rate of film growth in sulphuric-acid anodizing.

The conversion of a metal into its oxide usually involves a change in volume. The density of massive alumina is considerably greater than that of aluminium, but the apparent density of the coatings produced by the anodic oxidation process is not greatly different from that of aluminium. Anodic coatings are porous, and the porosity largely accounts for the low observed density of the film. It might be thought that the dimensional change which thus accompanies anodic oxidation would lead to the development of stress within the coating, but Bradshaw and Clarke,[10] from observations on the bending of aluminium strips anodized on one side only, conclude that the stress in these deposits is slight.

The anodic layer consists initially of alpha alumina which, on ageing or heating, e.g. in boiling water, is ultimately converted into gamma alumina. The porosity of the film varies with the nature of the electrolyte employed. The films produced in sulphuric acid are more porous than those produced in chromic acid; in the former case it is customary to immerse all work in boiling water following anodic treatment, to seal the pores and thus to increase the serviceability of the coating. The hardness of the film also varies with the method used for its production, and by choosing the appropriate working conditions, very hard films, possessing exceptionally good wear and abrasion resistance, can be obtained.

(4) ANODIZING PRACTICE

There are three established processes for anodically oxidizing aluminium and its alloys. The Bengough–Stuart process, invented in 1924,[13] employs a chromic-acid electrolyte. The alternative processes use sulphuric-acid and oxalic-acid electrolytes respectively. While there are practical differences between these processes, and while there are some variations in the characteristics of the films they produce, they are all fundamentally similar. The chromic-acid and sulphuric-acid processes are the ones most widely used, particularly in this country. The oxalic-acid process appears to have found some favour in Germany and in Japan.

(4.1) The Chromic-Acid Process

The electrolyte used in this process is a $2 \cdot 5$–$3 \cdot 0$% solution of chromic acid. This electrolyte does not attack steel, and it may therefore be contained in an unlined plain steel tank. Provision is made for heating the electrolyte at an initial temperature of 40° C and for agitating the whole of the bath to ensure that its composition remains uniform and that gas evolution is in no way restricted. The tank itself is used as the cathode, or alternatively stainless-steel cathodes may be suspended in the electrolyte. The recommended cathode/anode area ratio lies in the range 5 : 1 to 10 : 1. The tank must have exhaust ducts capable of extracting not less than 200 ft^3 of air per minute per square foot of surface area.

The standard chromic acid process cannot be operated co

uously; work has to be treated in batches. Cyclic operation necessary because the voltage at the commencement is much ver than that at the termination of the treatment. As treatnt proceeds the resistance of the film increases progressively. keep pace with the change in resistance and to maintain an proximately constant current density (1–5 amp/ft^2), the tank tage must be varied, the standard procedure being to increase voltage from 0 to 40 during the first 15 min of treatment, to intain it at 40 for the next 35 min, to raise it to 50–60 during ensuing 5 min, and to maintain it at 50–60 for 5 min. The al time of treatment is thus 60 min. The average energy nsumption for this process is about 0·2 kWh/ft^2.

In view of the relatively high voltages reached in this process d because the use of a conducting tank is common practice, ecautions must be taken to guard against electrical leakage. s recommended that the tank be insulated on glass or porcelain cks, or on hard wood soaked in paraffin. The films produced this process are opaque and grey in colour. The average ight of the film is about 3 g/m^2. Sealing of the film is not cessary, although a quick dip in boiling water is sometimes voured. As in all of these anodizing processes, some aluminium solves in the electrolyte as the treatment proceeds. Chromic d is thus slowly consumed by conversion into aluminium romate, and additions of fresh acid must be made to effect a mpensation. Rejuvenation in this way cannot be carried to remes, however, as the gradual accumulation of aluminium romate in the electrolyte progressively inhibits the anodic idation process.

(4.2) Uses and Limitations of the Chromic-Acid Process

The main advantages of this process are its versatility and the n-corrosive characteristics of the electrolyte. Because chromic d is inert towards aluminium in the absence of current, it n safely be used as a medium for anodizing assemblies with evices and joints from which it would be impossible to remove ery trace of electrolyte in the rinsing operation.

The films obtained are thin, the thickness being of the order 0·0001 in. There is little loss of metal, and the dimensional ange amounts to a growth of only about 0·00001 in. The gh working voltage employed is said to assist the deposit to row well into deep recesses, and Wallbank[14] in consequence ys that greater liberties can be taken in the methods of susnding the work in the electrolyte than are permissible with the lphuric-acid process. Compared with the latter the main sadvantages of the chromic-acid process are (*a*) that it cannot oduce thick films, (*b*) that it cannot be operated continuously, that it is slow, (*d*) that it is not entirely suitable for the odizing of alloys containing high percentages of other metals ch as copper and silicon, and (*e*) that the film it produces is aque and non-metallic in appearance. The introduction of a odified half-hour process, which produces films little less otective than those obtained by the standard one-hour process, s, to some extent, overcome some of these objections.[15]

While the films produced by this process afford good protion, they are less attractive in appearance than those obtained the sulphuric-acid process. Moreover, the appearance of the n is influenced, not only by the composition of the metal ing treated, but also by its crystal grain size and orientation. loys containing 4% or more of copper when treated in chromic d form dark films of relatively poor protective value. Highcon alloys are difficult to treat because they necessitate the e of a very high bath-voltage.

(4.3) The Sulphuric-Acid Process

In this process the work is treated anodically in a 10–20% lution of sulphuric acid at a temperature of 20°–25° C, using direct current at 10–20 volts. The current density is 10–20 amp/ft^2, and the time of treatment is 10–60 min, according to requirements. The anodizing tank is conveniently made of mild steel lined with sheet chemical lead with burnt joints. The lead lining of the tank may be used as the cathode, or, if preferred, separate lead cathodes may be suspended in the solution. The tank must be suitably insulated against electrical leakage to earth.

As the Joule effect of the current is more than sufficient to keep the electrolyte at the working temperature, cooling coils made of lead pipe must be placed in the electrolyte. Except in warm climates, some means of heating the electrolyte to 25° C must be provided.

The attraction of this process, and the main reason for its popularity, lies in its ability to produce a thick transparent anodic film fairly quickly and in the flexibility which it affords the operator in respect of modification of the properties of the film to suit specific requirements. The properties of the film are related to the four variables, electrolyte concentration, working temperature, anode current density, and time of treatment. Many combinations of these variables are clearly possible, and once the conditions to meet a particular specification have been established they must be closely controlled. In all events, precise temperature control and uniformity of temperature throughout the electrolyte must be maintained. To this end, agitation of the electrolyte, which is also necessary to eliminate concentration gradients, is essential.

Following the anodizing, the film must be sealed to increase its corrosion resistance and to render it non-absorptive. The exact mechanism of the sealing process does not seem to have been established beyond all doubt, but it is generally believed that sealing converts the outer layer of the anodic film into a crystalline mono-hydrate of alumina. Sealing is effected either by immersing the work, after thorough rinsing, in boiling water for 20–30 min or in a 5% solution of potassium dichromate for 15 min. The latter process imparts a yellow colour to the film but gives a coating of maximum corrosion resistance, and hence is favoured for sealing anodized work that has to withstand severe corrosive conditions. It is especially useful for castings, as it nullifies the effect of porosity in so far as retention of electrolyte within the pores is concerned.[16]

The sulphuric-acid process is quite suitable for the treatment of aluminium alloys containing high percentages of copper. It cannot be used with safety for anodizing any articles whose design precludes the removal of all traces of electrolyte during the rinsing. Sulphuric acid attacks aluminium, even in the absence of current, and any entrapped electrolyte will consequently soon lead to serious local corrosion.

By this process it is quite easy to obtain films of thickness 0·0005 in. The energy consumption varies from 0·05 to 0·25 kWh/ft^2, according to the duration of the treatment and hence according to the thickness of the film. The maximum consumption is thus approximately the same as that for the chromic-acid process.

(4.4) The Oxalic-Acid Process

This process resembles the sulphuric-acid process rather than the chromic-acid process. It is less used than either of these, and it is not proposed to discuss it in any detail. Like the sulphuric-acid process it produces transparent films, but unlike that process the films have a yellowish colour. One objection to the process is the relatively high cost of the electrolyte.

Anodizing is now widely used for the protection and decoration of aluminium. In recent years great improvements have been made in the dyeing of anodized films and a wide variety of coloured finishes is now available. These decorative finishes are hard and durable; they are pleasing to the eye, the golden

finishes in particular being most attractive. Anodizing is not confined to the surface conditioning of aluminium for corrosion resistance or for aesthetic appeal. Important other uses of the process are for increasing the abrasion resistance of aluminium and its alloys and for rendering these materials sensitive to light to enable photographic images to be impressed on them. A specialized application of the use of anodic oxidation for protection is in connection with electrolytic brightening in the manufacture of aluminium reflectors.

(5) ANODIZING FOR WEAR RESISTANCE

While a hard film is clearly required to counteract wear and abrasion, hardness *per se* is not the only property of the film that has to be considered. In most engineering applications of anodized aluminium, some lubrication is likely to be provided, and for lasting service the anodic film should be able to absorb or adsorb the lubricant. Moreover, the film must not shed abrasive particles when subjected to frictional forces, while it must be strong enough to withstand service conditions without cracking or flaking.

It has already been intimated that the properties of films obtained from the sulphuric-acid electrolyte vary with the operating conditions. Studies have been made of the effect of the variables of the process on the hardness of the anodic film.

The sulphuric-acid bath and the oxalic-acid bath produce harder films than the chromic-acid bath; the hardness of the films is greater when the current is direct than when it is alternating and increases as the temperature of the electrolyte is reduced. Also, moderately thick films tend to exhibit maximum hardness.[17] The hardness of the film varies with the concentration of the electrolyte, but the optimum concentration for maximum hardness is apparently related to the working temperature.

The degree of hardness that can be obtained depends also on the composition of the aluminium alloy. For example, under a given set of conditions, harder films can be obtained on aluminium–magnesium alloys than on aluminium–copper alloys. There is also some evidence that, for some alloys, notably for those containing copper or silicone in considerable amounts, anodizing with alternating current superimposed on direct current gives harder films than does anodizing with direct current alone, which is the usual procedure in anodizing practice.

The demand for thick hard anodic films to give increased resistance to wear in engineering applications has stimulated interest in so-called hard anodizing, and in recent years modified processes have been introduced to meet this demand. One such patented process, described in some detail by Campbell,[18] is claimed to provide an ideal finish on sliding surfaces such as valve faces and to effect substantial reduction in the rate of wear of the basis metal in numerous other applications. For engineering purposes the film thickness required is 0·003–0·004 in. Smoothness appears to be an important criterion of wear resistance, the coefficient of friction falling as the smoothness of the film increases. As deposited, the film may show height variations of 30–50 microinches, but by honing or lapping this figure can be reduced to 3 microinches. The corresponding improvement in the coefficient of friction, according to Campbell, is from 0·3 to 0·11. The salient features of the process described by this author are the use of a cold electrolyte and operation with alternating current superimposed on direct current. The ratio of a.c. to d.c. depends on the composition of the aluminium alloy, on the degree of agitation of the electrolyte, and on other factors. By superimposing a.c. on d.c., harder films are obtained and at the same time a stabilizing influence is exerted on the anode, i.e. the work, preventing it from suddenly becoming depassive and therefore susceptible [to] rapid anodic dissolution, as is liable to occur with high un[i]directional current densities. The anodizing may be done [in] oxalic acid or in sulphuric acid. Oxalic acid gives the smooth[est] films, but the higher conductivity of sulphuric acid is much [in] its favour as the lower heat dissipation for this electroly[te] greatly reduces the difficulties of refrigeration. As the recom[]mended bath temperature is $-4°C$ to $+4°C$ it will be appr[e]ciated that heat abstraction becomes quite a problem wi[th] poorly conducting electrolytes. In small plants, cooling may [be] effected by pumping a refrigerant through stainless-steel cooli[ng] coils immersed in the electrolyte, but for large units it may [be] simpler to pump the electrolyte continuously to a separa[te] refrigerating unit.

It will be apparent that the electrical power-supply unit f[or] operating this type of plant is considerably more complicat[ed] than that for the straightforward process. Some possible circu[it] arrangements, redrawn from Campbell's paper, are shown [in] Fig. 2. Method (*a*) is recommended for small plants of up [to]

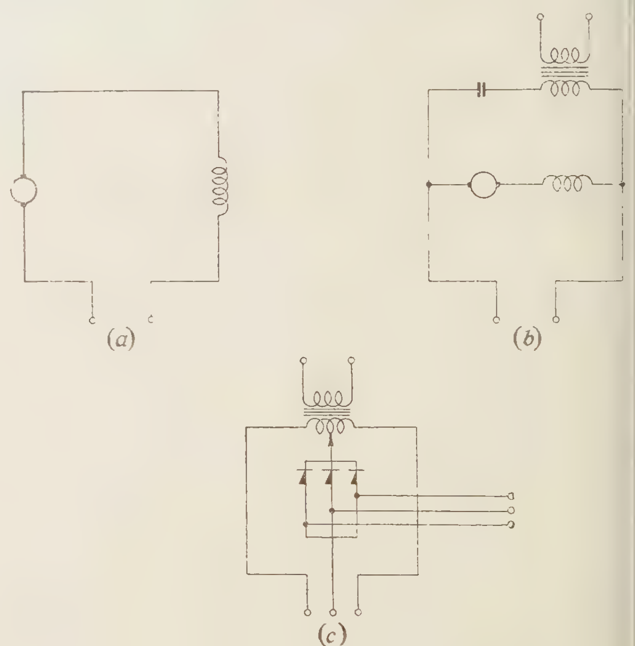

Fig. 2.—Circuits for the anodizing of aluminium, using direct curre[nt] superimposed on alternating current.

100 amp capacity. The alternating current is injected throug[h] the coil, which forms the secondary of a 60-volt transforme[r]. Method (*b*) shows the transformer in series with a condens[er] and the generator in series with a choke; this arrangeme[nt] prevents the alternating current from saturating the transform[er] core and the direct current from affecting the generator winding[s]. Method (*c*) employs a 3-phase rectifier feeding into the centr[e] tap of the transformer secondary; the same arrangement can [be] used with a single-phase rectifier, but if the a.c. load is hea[vy] and the rectifier is fed from a transformer, three units shou[ld] be grouped, one on each phase, to obtain balanced loadin[g]. Research on the effect of frequency on the hardness of the fil[m] has suggested that the hardness increases with the frequenc[y], but so far the cost of producing alternating current at high[er] frequencies than 50 c/s has militated against their use. More[]over, it is stated that the improvement in film hardness resultin[g] from increasing the frequency from 50 c/s to 150 c/s can equal[ly] well and more cheaply be obtained by increasing the agitatio[n] of the electrolyte.

These hard anodic films are inelastic and fail by cracking if bjected to bending. The films adhere firmly to the basis etal, and provided the latter is not deformed, they stand up ry well to service conditions. Hard films can be sealed in the me way as the softer films, but immersion in boiling water ftens them. Impregnation with wax or oil is preferred if some ter-treatment is deemed necessary to increase corrosion sistance. As would be expected, hard anodizing leads to some minution in the fatigue strength of the basis metal, but this n be taken into account by designers when it is a matter of fficient importance. By knowledgeable application of the ocess and close co-operation between the designer and the odizer, the fall in fatigue strength can apparently be reduced an acceptable minimum.

While all operators of sulphuric-acid anodizing plants are vare that they can alter the hardness of the anodic film within nits and that certain alloys will give harder anodic films than hers, the deliberate production of hard anodic films by prosses such as that just described is a comparatively recent velopment. Although there is now a considerable amount of ta available on the properties and behaviour of such specially epared films, it is still rather early to say just how far their here of usefulness is likely to extend. Hard anodizing is ndoubtedly attracting much interest, and the indication is that e use of anodizing to increase resistance to wear and abrasion ll steadily increase.

(6) ANODIZING FOR PHOTOGRAPHIC REPRODUCTION

It was shown many years ago that the anodic film on aluminium uld be made sensitive to light by impregnation with a photonsitive emulsion. After sensitization, patterns or images can printed onto the film by direct contact with a negative carrying e desired design and exposure to light, just as in ordinary otographic practice. The work is then developed and fixed hypo in the usual way. All of the tricks of photography, ch as toning with gold salts, can be applied to the film. Finally, e film can be polished, and it then provides a hard glossy production on the aluminium.

Extensive use is now made of this process for such purposes the making of name-plates, watch and instrument dials, slide les, calendars, etc. The process is cheap to carry out and nsistent in its results. The finish obtained, after sealing, is rable and wear resisting. If desired, colours can be introduced dyeing the unexposed portions of the film.

(7) ELECTROLYTIC POLISHING

The possibility of brightening a metallic surface by selective odic dissolution was first demonstrated nearly twenty years o. Early work was mainly confined to the polishing of copper, t other metals and several alloys can now be polished by the ctrolytic process.

There still appears to be some doubt as to the true mechanism electrolytic polishing, although sufficient information has en obtained experimentally to enable the theoretical conditions be postulated with some accuracy. Jacquet[19] has shown that, the electrolytic polishing of copper in phosphoric acid, a n viscous film forms over the surface of the metal which in ne manner retards dissolution at depressions and facilitates ack at elevations where the anodic current density exceeds the erage value. Elmore[20] has confirmed the existence of such a n and concludes that the rate at which the copper is dissolved governed by the rate of diffusion of cupric salts away from the ode. Polishing only occurs over a part of the anode currentnsity/potential curve and is always associated with the presence the viscous film.

Many different polishing electrolytes have been suggested, some of which apparently give considerably better results than others. In an attempt to explain this difference in behaviour and to find out more about the composition and properties of the viscous layer, Walton[21] has studied the behaviour of copper in electrolytes consisting of mixtures of phosphoric acid with glycerol and ethylene glycol, as well as in phosphoric acid alone. He concludes that the polishing action is due to the presence of a viscous layer which controls the rate of dissolution, partly by virtue of its varying thickness. At surface elevations, where the film is thin and the concentration gradient is high, diffusion is rapid and there is less stifling of dissolution than at low spots, where the thicker film retards the diffusion of the dissolution product and thus slows down the anodic attack. It is concluded that the process is governed primarily by the diffusion characteristics of the film and not by its electrical resistance. Walton has estimated the thickness of the anode film to be 0·006 cm. For effective polishing he advises that the thickness of the film should be about the same as the height of the irregularities that it is desired to remove. Under these conditions the best compromise between the speed and efficacy of polishing is said to be obtained. The film should be thin and tenaciously adherent to the anode; it should have a relatively high viscosity, but the electrolyte itself should for preference have a low viscosity. As the viscosity of the electrolyte increases so also does the operating voltage, while drag-out losses becomes greater.[22]

(7.1) Advantages of Electrolytic Polishing

Conventional polishing by rotating mops is expensive, and an outstanding advantage of the electrolytic process is the saving in labour costs which it affords. The attractiveness of this process will obviously increase as the difficulty, and hence the cost, of mechanical polishing becomes greater, It is not surprising, therefore, that particular attention has been devoted to perfecting the electrolytic polishing of stainless ferrous alloys, as these materials are troublesome to polish by other means. Saving in cost is not, however, the only advantage of the electrolytic process. There are many instances in engineering, for example in electronic engineering, where the shape of the article that has to be polished renders mechanical finishing impracticable or even impossible. There are also instances where the polished surface is required to be stress-free, and such a requirement can be very difficult to meet if the polishing is done mechanically. There is a fundamental difference between mechanical polishing and electrolytic polishing in that the former tends to produce an amorphous surface film on the work, whereas the latter merely dissolves away the irregular surface of the metal differentially until a level surface is obtained. Electrolytic polishing does not therefore alter the structure of the basis metal or alloy, and it is partly for this reason that it is so useful to the metallographer for the preparation of his specimens, revealing their true structure.

(7.2) Range of Application

Many metals and a number of alloys can now be polished electrolytically. Single-phase alloys do not generally present much of a problem, but 2-phase alloys are not so amenable to polishing in this way unless the difference between the electrode potentials of the phases with respect to the polishing electrolyte is small. Edwards[23] points out that the polishing of 2-phase alloys is in any case likely to call for closer control than is needed in the polishing of pure metals and single-phase alloys, and that, even if phase potential differences could be entirely suppressed, lengthy polishing might lead to height differences resulting from differences in the densities and electrochemical equivalents of the respective phases. The chances of success in

polishing alloys can sometimes be increased by paying careful attention to correct adjustment and control of their composition, as is now being realized in the electrolytic polishing of brass. As progress is made, the number of alloys that can be polished electrolytically is constantly increasing, and there is no evidence that the limit has yet been reached.

(7.3) Equipment and Procedure

Electrolytic polishing in practice is not greatly dissimilar from electroplating insofar as plant and equipment are concerned. Current densities are usually high, as in chromium plating practice; most metals can be polished at anodic current densities not exceeding 250 amp/ft^2, but considerably higher current densities are not uncommonly employed. The voltage required will depend on the resistance of the electrolyte, and is usually from about 10 volts upwards. When heavy currents are involved some thought must be given to the method of making contact with the work. High contact resistance can lead to local overheating and possibly to electrolytic effects which would damage the surface. Proper design of supporting jigs and assurance that they are of adequate cross-section to carry the current without overheating obviates such trouble. As the jigs themselves are anodic they will naturally tend to dissolve unless they are either protected by suitable insulation or made of a metal which, by its nature, becomes passive when anodically polarized in the solution in which it is used. Thus, a bath has apparently been developed for polishing stainless steel in which copper becomes passive and the work can therefore safely be suspended from copper jigs.[24] Stopping off with a suitable resin is the more usual practice, however, and is also resorted to when areas of the work itself are to be protected from the anodic attack.

The electrolytes used for electrolytic polishing are characterized by their ability to cause rapid and high polarization at the anode. Polarization is possible in many different solutions, but only a limited number of these, mostly acid solutions, are practicable for polishing on an industrial scale. The water content of the electrolyte appears to be somewhat critical.

Dilution by adding water reduces the cost of the electrolyte and increases its conductivity but simultaneously increases the difficulty of obtaining a true polish without etching the surface of the metal. A compromise has to be effected, and the most popular electrolytes are those for which the water content is the least critical.

Treatment tanks are usually made either of steel lined with lead or some other inert material or of stainless steel. If of large capacity they must be adequately braced to withstand the hydrostatic pressure of the electrolyte. Cathodes are of copper, lead, nickel or stainless steel, according to requirements. The usual practice is to place cathodes on two opposite sides of the work and to keep the inter-electrode distance small. Provision is usually made for heating and for cooling the bath, but the low conductivity of polishing electrolytes leads to considerable generation of heat, and intelligent use of this heat usually enables the temperature of the solution to be maintained at the correct value without much forced heating or cooling. Means for agitating the electrolyte and for the exhausting of spray must be provided. The auxiliary equipment required, pumps, filters, storage tanks, and so on, does not differ much from that used in electroplating practice.

The time of treatment depends on the amount of metal that has to be removed, and hence on the degree of smoothness of the original surface. In the interests of economy it is clearly desirable that the work should be as smooth as possible, and to this end inexpensive preparatory treatments such as shot blasting are sometimes advantageous. The amount of metal that has to be dissolved is small and may be as little as 0·0001 in. According to the initial smoothness of the metal surface, the nature of the electrolyte, the current density and the bath temperature, the average processing time ranges from about 8 min to 30 min.

(7.4) Industrial Practice

Many polishing electrolytes have been suggested since the process was first invented, but experience has shown that relatively few solutions are suitable for commercial use. Most of the solutions in use to-day are based on sulphuric acid and phosphoric acid. A process employing such an acid electrolyte, patented in this country in 1939,[26] has proved very attractive for a variety of work and has developed rapidly in recent years. The mixed-acid bath used in this process, which may also contain chromic acid, is nowadays generally preferred to straight-acid baths, e.g. phosphoric acid. For polishing stainless steel, sulphuric-acid/phosphoric-acid and sulphuric-acid/citric-acid electrolytes give better results, according to Faust,[25] than straight phosphoric-acid electrolytes. Sulphuric-acid/phosphoric-acid electrolytes have a wide working current-density range and can also be used for polishing carbon and low-alloy steel. Alternatively, carbon and special steels can, it is claimed, be polished in phosphoric-acid/chromic-acid electrolytes. An interesting development is the use of the latter for super-finishing, by which is meant finishing the work to very close dimensional tolerances over the whole of the polished surface. In this modification of electro-polishing the treatment time is reduced and the voltage and current are increased, the former up to 35 volts and the latter to 1 000 amp/ft^2 or even higher. Electro-polishing has been applied to steel valve springs and turbine blades, to assist inspection. The process reveals defects not otherwise easy to detect and is also beneficial in removing the surface decarburization which is commonly present on spring steel and is a cause of reduced resistance to alternating stress.[27]

Nickel can be polished in straight sulphuric acid, but the addition of phosphoric acid to the bath is claimed to widen its working current-density range. Copper, one of the first metals to be electrolytically polished, can be polished in phosphoric-acid/chromic-acid solutions or in phosphoric acid alone, as was originally recommended by Jacquet. For industrial work Faust prefers phosphoric acid containing a small amount of a permanent addition agent on the grounds that this solution operates at a more easily maintained composition and at a more practicable temperature level than the mixed-acid bath. On the other hand, phosphoric-acid/chromic-acid electrolytes are preferred for the polishing of brass, as the operating temperature is 60° C, whereas in straight phosphoric acid brass can be polished satisfactorily only if the temperature of the bath is kept so low that refrigeration becomes necessary. Aluminium and its alloys can be polished in sulphuric-acid/phosphoric-acid/chromic solutions. Alloys are more difficult to polish than is the pure metal, and silicon-containing die-casting alloys cannot be polished in this solution.

Owing to its high reflectivity, aluminium is widely used in the manufacture of reflectors. A highly reflecting surface can be imparted to this metal by a dual anodic process in which two electrolytes are employed successively.[28] The process is more in the nature of electrolytic brightening than of polishing, as the surface is fairly bright at the outset. The two stages of the process are (*a*) the production of the reflecting surface, and (*b*) the application of a protective layer to prevent deterioration of the reflectivity in service. After preliminary polishing, the natural oxide skin on the metal and all traces of contamination must be removed, as otherwise the full reflectivity cannot be developed. This is achieved by immersing the work in the electrolyte, which contains sodium carbonate and trisodium

osphate and is maintained at a temperature of about 80° C, thout applying current. Vigorous etching occurs and is owed to proceed for 10–30 sec, the time depending on the rity of the metal. At the end of this period, direct current at out 10 volts is applied, the work being made anodic. The itial current density is about 60 amp/ft^2, but soon falls towards amp/ft^2 as the anode film is formed. Etching ceases within sec after the current has been switched on; anodic treatment continued for 5–8 min, the time increasing with the purity the metal. The work is then withdrawn and rinsed immediately water. It now has a bright surface, but the finish is too thin withstand wear and it must therefore be reinforced and otected. This is done by a further anodic treatment in an ueous solution of sodium bisulphate operated at 35° C and a current density of 5 amp/ft^2, the time of treatment being min. The work is finally rinsed in cold water, immersed in t water for 15–20 min, dried, and sealed by the application of ax. Alternatively, reflectors made from super-purity aluminium n be sealed by polishing on a soft mop charged with a suitable ishing compound.[29]

(7.5) Economies of Electrolytic Polishing

The two major cost factors in this process are (*a*) chemicals,) electrical energy. The latter will vary with the time of eatment, the resistance of the electrolyte, the current density, e efficiency of a.c.-d.c. conversion, and the cost per kilowatt-our. The cost of chemicals cannot be estimated accurately, as ag-out loss is an unknown factor.

In the polishing of stainless steels, Charlesworth[22] estimates ese costs as follows:

	Pence per square foot
Electrical costs	0·1–1·0
Chemical costs	0·2–2·5

etal is lost by dissolution in this process, but this occurs also mechanical polishing. Charlesworth states that the amount metal normally removed in polishing stainless steel varies from 000 25 in to 0·001 5 in, while mechanical polishing removes 002–0·005 in. He points out that, while the metal lost in echanical polishing processes is not readily recoverable, that ssolved in the electrolyte in anodic polishing could be recovered om the solution if it were economically worth while to do so. e suggests that such recovery might be considered in the case steel works handling large quantities of material.

(8) CONCLUSION

The war delayed the development of electrolytic polishing, d, so far as this country is concerned, marked industrial ogress in this field has only been made in the last few years. ectrolytic polishing is no panacea for poor and defective rface finish, and following the cessation of hostilities the rface quality of metals in many cases had to undergo improve-ent before the new process could with advantage be adopted. e advantages of the new process were ultimately appreciated d its future seems to be firmly assured. It is proving a valuable l to production and indeed, in some instances, is leading to sults which would be almost impossible to achieve by older, nventional metal-finishing procedures.

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Paper No. 1
Oct. 1

THE ELECTRICAL EQUIPMENT OF THE TORONTO SUBWAY CARS

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SUMMARY

The paper deals with the 600-volt rolling stock designed and built in England to the order of the Toronto Transportation Commission in Canada (since reconstituted as the Toronto Transit Commission), whose new underground electric railway is now in passenger service. The traction equipment is described, together with the arrangements for the collection of power by the trains and its distribution in them. Particular reference is made to the provisions for the safe return of current to the rails. The low-voltage auxiliary equipment is described, and the extensive arrangements for coach heating and ventilation are set out; the electro-pneumatic braking system and door control are also detailed. The descriptions are preceded by a survey of the traffic problems of the city of Toronto and the decisions taken to expedite the movement of its urban passengers. The paper closes with a few comparisons with similar stock elsewhere and gives numerical data in an Appendix.

(1) INTRODUCTION

(1.1) Traffic Requirements

The new underground electric railway in Toronto, the first in Canada, runs under the city's main traffic artery from its northern outskirts to the main-line station in the heart of its business centre. First opened to the public on March 30th, 1954, this enterprise represents a combination of years of painstaking planning in Canada, a high degree of collaboration between British designers and careful manufacture of rolling stock in England. The necessity for such a subway was clearly demonstrated in 1942, when an analysis of the population trend in Toronto was made and the character of its street traffic was examined.

The city itself is in the shape of the capital T inverted, its head standing on the shores of Lake Ontario (see Fig. 1). The area of the city is about 35 square miles within which is contained three-quarters of the population of the metropolitan area of Toronto. The lake frontage is of the order of 11 miles, with a depth of about $3\frac{1}{2}$ miles, while the length of the centre leg of the T is approximately 7 miles. In 1953 the officially assessed population figure for metropolitan Toronto was 1 172 556 and the trend since the beginning of the century is shown in Fig. 2; at the end of the 1939–45 War the city planning board expected the figure to reach 1 500 000 by 1974, but this may well prove to be an underestimate. The growth of population has been steady and has not been much influenced by trade advances or recessions—this no doubt being due to the wide variety of industry and commerce in the city. Automobile ownership has reached an average of one car for less than every four persons, and the traffic congestion is such that, in 1946, it was estimated that the average speed in the rush hour was only 6m p.h. While the bulk of traffic still flows north and south, originally the streets were laid out for horse-drawn vehicles, with only one major continuous north-south street linking the commercial lake-side part of the city with the populous northern subu Before the advent of the subway all public transport was street level, and it had been estimated that half the passeng of all types were having to change between vehicle routes least once to reach their destinations.

To the above data the Toronto Transportation Commissi (T.T.C.) added their estimates of the probable traffic in foreseeable future on the important north–south artery (Yor Street) and also on the east–west thoroughfare (Queen Stree they also analysed the existing road services, which include fleet of streetcars, petrol- and oil-engine omnibuses and troll buses. Their decision was that the best way to relieve congesti and afford a convenient and speedy method of transit was construct an underground railway system with provision passenger movement to reach ultimate peaks of 40 000 passeng per hour on Yonge Street and 15 000 on Queen Street. In orc to relieve the congestion on these streets and at the same ti provide facilities for the rapid movement of the passengers, was decided that transport should be arranged on reserv tracks either beneath the streets or, where buildings permitt to one side of them. It was thought that the loading and u loading of vehicles would be accelerated if platforms at stops were at the floor height of the cars, thus eliminating steps previously required to enable road passengers to mou from street level. The peak traffic on Yonge Street was alrea greater than could be handled by surface transport, even wh this consisted of streetcars on reserved track, but for the prese the Queen Street traffic can still be operated by fast streetca Accordingly, the T.T.C. adopted a 2-stage plan of improveme

(1.2) Proposals

On a long-term basis the T.T.C. decided to separate the tra port system of the city into two sections, one being on the str and the other off the street. Subways were to be construc running north and south, also east and west. In the cent part of the city these were to be built on the "cut and cov system, but in the outlying districts, where property was chea to acquire and where there was more vacant ground, the s ways were to be of the "open cut" type. New multiple-u electric rolling stock was to be purchased. The proposed tra facilities are shown in Fig. 1.

On a short-term basis it was decided to construct the no south rapid-transit subway system along Yonge Street imr diately and to purchase special rolling stock for it. The subw being completely new, the designers of all parts of the equ ment, ranging from civil engineering through signalling to roll stock, enjoyed the benefit of being unhampered by any neces for running in parallel with existing equipment, except tha was felt desirable to retain the local track gauge of 4ft 10 This section of the plan is now in service. Intermediate betw the long- and short-term proposals was the intention to constr the east–west Queen Street line as soon as the Yonge Str section was in service, but to operate with Presidents' Confere Committee (P.C.C.) streetcars of the type already in use in city. However, the subway was to be made of such a size t multiple-unit stock similar to the other system could later

This is an "integrating" paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

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Fig. 1.—Map of route.

Rapid-transit subway.
Surface-car subway.
Surface-car routes using subway.

sed in it. At present, financial stringency is postponing this hase, but with an eye to the future the short length of the Queen treet line lying immediately beneath the Yonge Street route as already been built as a part of the civil-engineering contract r the latter.

Each of the two lines has a route length of about $4\frac{1}{2}$ miles. the north–south direction a schedule speed of $17\frac{1}{2}$m.p.h. at eak periods is provided, but it is thought that operation on the st–west route with P.C.C. streetcars will be acceptable initially.

(2) GENERAL DESCRIPTION

(2.1) System

The Yonge Street subway operates between its southern rminal at Union Station and Eglinton in the north, but the ute can be extended further northwards if the need should ise. At the southern station there are interchange facilities th the main-line railway station, which serves both important anscontinental and suburban areas. From here the subway ns east–west for some 150ft before swinging round its only preciable curve—of 408ft radius—onto its north–south alignent. . Interchange facilities are freely provided to connect with

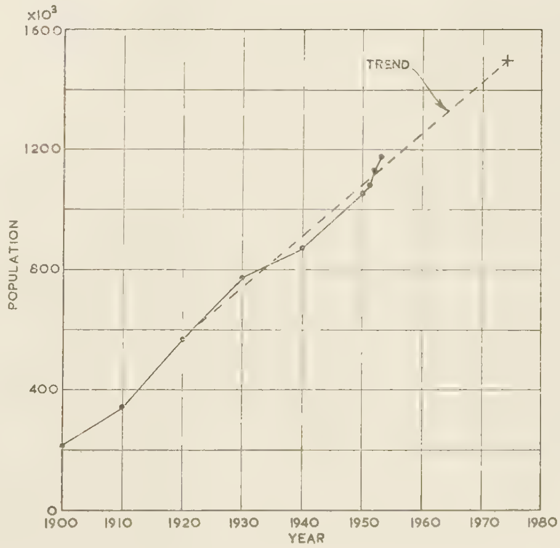

Fig. 2.—Population of metropolitan Toronto.

surface transport at all stations, and some have covered loops or bays for omnibuses, trolley coaches and streetcars. Beyond the southern terminal are 400 ft of storage track; including these, the overall route length between bulkheads is 4·57 miles, of which 2·90 miles are underground and 1·67 in the open. Some ten acres of land are occupied by a depot and running sheds at Davisville, near the northern terminal; from the depot there is an overlap or gauntlet connection to the standard-gauge main line of the Canadian National Railways. A route diagram is included in Fig. 3 showing the locations of the twelve stations on the line.

The topography is favourable, the maximum gradient is about 1 in 30 ($3\frac{1}{2}\%$) and is not long; the ground rises steadily from the lakeside in the south, so that the northern terminus at 500 ft elevation is 265 ft above the southern terminal at 235 ft. Hence the average gradient is approximately 1 in 90 (1·1%). Fig. 3 includes some details of these gradients, which present no great difficulties to modern multiple-unit electric stock, particularly since the track is almost straight with only one severe curve through 90°. The route followed involved subway construction beneath the southern end of Yonge Street, where the subsoil is chiefly sandy clay, blue clay and a mixture of sand and gravel; a short length is through Dundas shale. The northern section had no peculiarities.

The southern cut-and-cover section of the 2-track route was built as a reinforced box-shaped concrete structure with an internal overall width of 32 ft 6 in, except at stations, but the presence of a central supporting wall 18 in thick gives the appearance of a twin-tunnel construction. Beneath Yonge Street the top of the roof is in places only 6 ft below the road surface, but there is 13 ft headroom inside. Third-rail top-running current-collection rails are used, but in the future Queen Street subway the roof height will permit P.C.C. cars to operate with overhead trolley collection in its early stages. The northern section of the system is of normal open-track construction and almost entirely in cuttings.

Station design varies with the depth of the track below the neighbouring street; 15 escalators in all are installed at seven stations, with provision for more if needed. Terminal platforms are islands 24 ft wide, but at intermediate stations, 12 ft-wide side platforms unobstructed by roof columns are used; all are 500 ft long. Many of the stations require artificial light throughout the day, and fluorescent lamps supplied at 60 c/s were selected for their appearance as well as for their economy in energy consumption. They are mostly 40-watt single-lamp fixtures, and the illumination intensities are greater than those hitherto used in similar places elsewhere; for example, platforms, mezzanine and control areas have $7\frac{1}{2}$–12 ft-candles, stairways and escalators have 10–12 ft-candles and tunnels have 1 ft-candle. A lamp life of at least 10 000 hours is expected.

The track supply is nominally at 600 volts d.c. using 150 lb/yd third rails; two top-running shoe collectors are mounted on each bogie, but no power busline is carried through the trains. Signalling is automatic, basically of the 3-aspect colour type and supplemented with automatic trackside train stops to guard against the inadvertent passing of a red signal. Although the route is simple and without junctions, five cross-overs have been provided at strategic locations to enable trains to be reversed short of their termini if necessary. Full signal interlocking is provided to ensure complete safety in service. At track turn-outs to the depot and yard, semi-automatic signalling prevents conflicting train movements, but the actual operation of the points and signals is left to a signals operator, not a motorman. Automatic train dispatchers at termini assist in maintaining a close headway, the system being signalled for a maximum of 40 trains per hour.

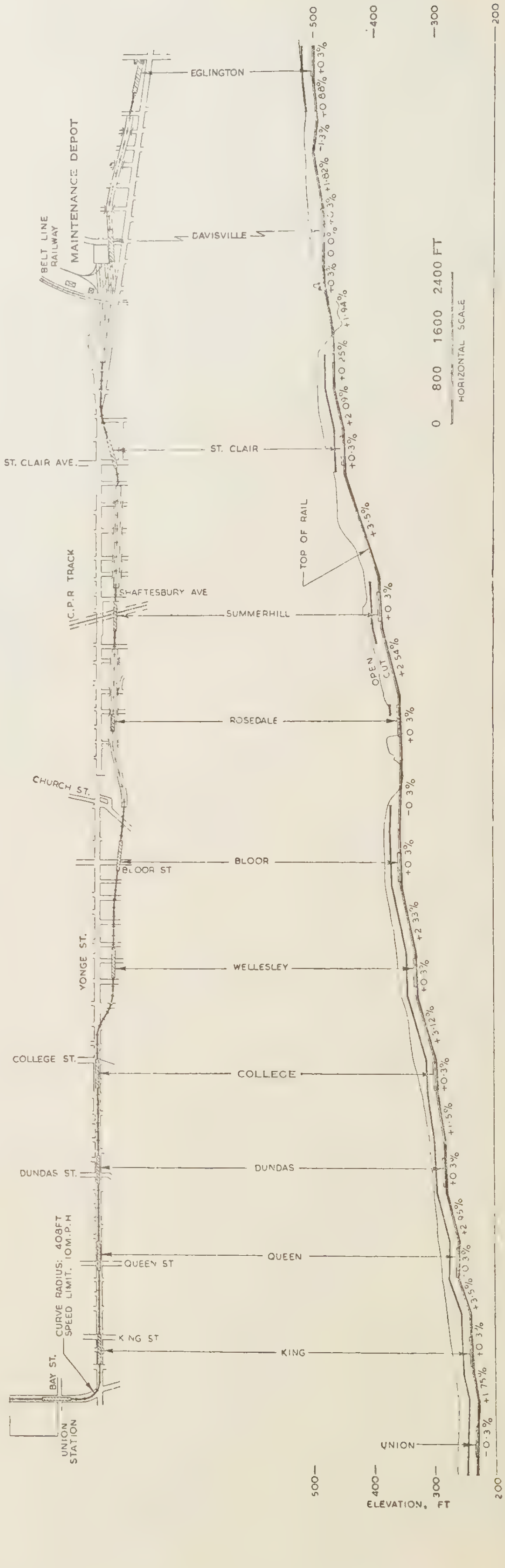

Fig. 3.—Plan and elevation of Yonge Street subway.

(2.2) Rolling Stock

Local familiarity with P.C.C. cars operating in the streets led to the initial proposal to use this type of stock for the Yonge Street line, but adapted for multiple-unit working. Planning therefore predicated the use of 10-car trains, each car seating 50 passengers. Eventually, however, it was decided to make up 8-car trains from longer 62-seat cars built in England. The designs drew on the accumulated experience of the London Transport Executive and of many other cities in Europe and America where large numbers of passengers had to be carried daily. The smaller number of longer cars has a total seating capacity approximately equal to the proposed 10-car trains, and it will be appreciated that the reduced number led to economies in capital expenditure and also in maintenance and storage requirements. These changes in plan were simplified by the absence of local railway standards restricting the choice of platform height, coupler height and car length; the structure could accommodate the revised vehicle lengths. On the other hand, with a view to the future operation of the Queen Street route, the track gauge was left unaltered at 4 ft $10\frac{7}{8}$ in. An illustration of a car as now running, showing its seating plan and the location of many components, is given in Fig. 4. Each car is identical in all respects save one, namely that alternate cars carry either a motor-generator with battery or a motor-driven air compressor; cars are designated A and B cars respectively. Every car has a single driving cab, pairs of cars being semi-permanently coupled together with the cabs outwards; automatic couplers are fitted to the cab ends of the cars. Accordingly, a 2-car unit is the smallest that can be operated and driven from either end. Up to four pairs can be coupled and used in multiple; more than four pairs can be coupled in an emergency, but the trains will then be longer than the platforms.

The bogies are of conventional design with four wheels, outside axle-boxes, $6\frac{5}{8}$ in-diameter axles and swing-link suspension. The driving arrangement is a departure from usual British practice since each bogie carries a pair of cardan-shaft-drive traction motors and high-ratio right-angle gearing. This layout removes the unsprung weight of the motors from the axles, while the high gear-ratio reduces their weight and size. The latter features, combined with the location of the motors, reduce the polar moment of inertia of the bogie, while the former, by eliminating axle suspension, considerably reduces the magnitude of lateral oscillation. Together these improve the riding qualities of the cars, and with the substitution of hypoid for spur gears, contribute greatly to quietness. Solid tyreless steel wheels of diameter 30 in when new, and $27\frac{1}{2}$ in when due for scrapping, are fitted. The design is such that replaceable tyres could then be fitted if desired, but it is unlikely that this will be done; future designs may omit this option. The bogies are equipped with unit brake cylinders acting individually on clasp brake-shoes. The leading bogie of each car is provided with a hand-operated parking brake acting on the same shoes and applied through a vertically actuated ratchet type of "pump" handle.

The underframe and body are designed to form a box structure or hollow beam which combines strength with lightness; since there is no truss, there is no obstruction underneath the floor to interfere with the location of the numerous pieces of equipment mounted there. The various steel sections and panels are jig-built by riveting and welding, the ends of the cars being strongly reinforced with anti-telescoping pillars and stiffeners; one of the latter is used to house the hand brake. Experience has shown the importance of having large and numerous doors to expedite the movement of passengers on underground railways; accordingly each car has three pairs of sliding doors per side, each door being operated electro-pneumatically. The leading dimensions can be gathered from Fig. 4 and from the Appendix.

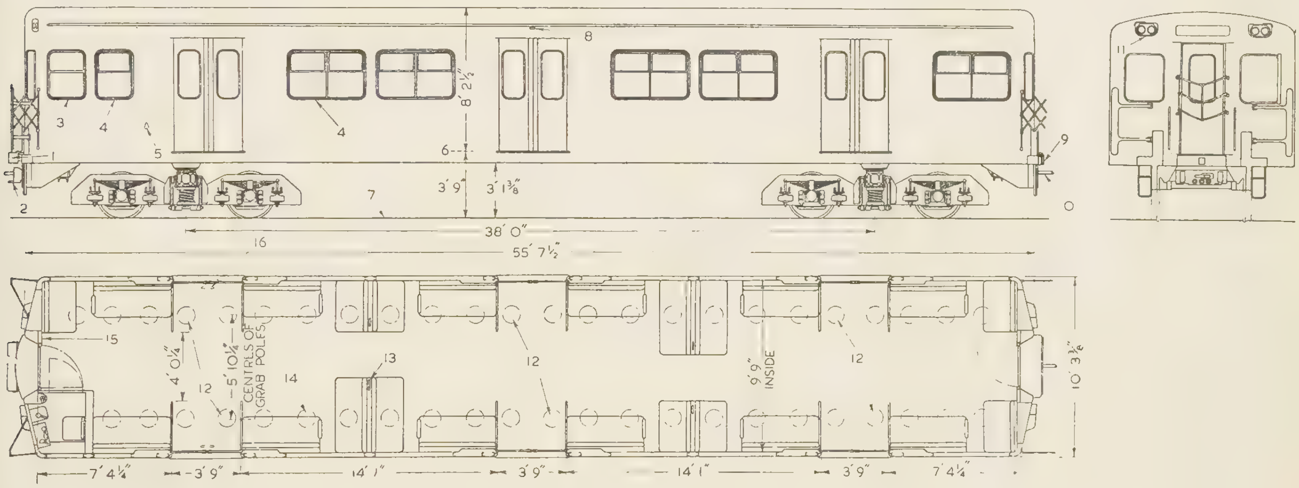

Fig. 4.—Plan and elevation of subway car.

1. Spring bumper.
2. Automatic coupler.
3. Full-drop window.
4. Half-drop window.
5. Key-operated staff switch
6. Floor level.
7. Rail level.
8. Door indicator light.
9. Dead bumper.
10. Bar coupler.
11. Marker lights.
12. Emergency lights.
13. Grab handle.
14. Light fittings.
15. Fire extinguisher.
16. Emergency door operator.

Inside the car, durability has been combined with numerous passenger amenities. The ceiling and sides are lined with plastic-faced panels, while upholstery and fittings are largely of aluminium covered with p.v.c. leathercloth or electroplated, these being durable finishes of attractive appearance which are also hygienic and easy to keep clean. A high level of illumination is provided by incandescent-filament lamps evenly distributed along the ceiling of the car. Ample heating is available within the cars, and dependent upon the temperature, a pressure ventilation system feeds heated or unheated air into the car through grilles incorporated in each seat frame.

Outside the car a smooth surface has been achieved with the sliding doors in pockets, as this simplifies the task of keeping the outside clean and also improves the appearance. Separate front marker and rear lights are fitted, as well as run-number signs and destination indicators illuminated on the end vehicles;

provision is also made for the addition of headlights if needed later.

(2.3) Capacity

If operated with 8-car trains at 2-min headway, the railway has a capacity of 14 880 seated passengers per hour; additionally, the cars are structurally designed for severe crush loading at peak hours—corresponding to about 40 000 passengers per hour. This not only appreciably exceeds the previous streetcar peak capacity of 14 000 passengers per hour, but also has a reasonable margin for the predicted growth of Toronto in the future.

(2.4) Performance

Since the objective was to treble the previous peak capacity of the system, the performance had to be lively; but since the route is essentially uphill in one direction, the southbound timing is faster than the northbound. Performance is independent of the number of cars in a train, for each car has its full complement of traction motors, and is nearly independent of passenger loading, since the driver has the choice of three accelerating currents. He can therefore select the one most nearly giving the required acceleration; automatic adjustment is provided to ensure that the maximum rate of braking is also sensibly independent of load. The brief period of free-running speed after acceleration is dependent upon, amongst other factors, the load carried.

Trains accelerate at an average of 2·3 m.p.h./sec on level track, maintaining this up to approximately 12·5 m.p.h.; two stages of field weakening then follow, and where track conditions permit, the free-running or balancing speed may be approached. Braking is preset to give a maximum retardation of approximately 3·0 m.p.h./sec on an equivalent straight-line basis, but any lower rate is available at the driver's discretion. The summer schedule for 1954 represents an average speed of about 17 m.p.h. northbound and 17·5 m.p.h. southbound, including station stops, but excluding layovers. The round-trip schedule speed including a 3-min layover at each terminus is 14·5 m.p.h. Actual station-stop times range from 9 to 34 sec, averaging 20 sec in peak hours and 12 sec at other times. The calculated balancing speed of a loaded train on straight and level track is 46·5 m.p.h., but only 650 ft of track are free from gradients. In comparing these speeds with those obtained elsewhere, it should be noted that the average distance between stations is only 2 145 ft. The future interchange point with the yet unbuilt east–west Queen Street route is at Queen station; this key point can be reached from the northernmost terminus, Eglinton, in 12½ min, stopping at all stations.

Accelerating current varies with passenger loading, as already mentioned, and the values with the pertinent car weights are given in Table 1. On the basis of the median value, the average accelerating current for a train of eight cars with the motors grouped in parallel is 4 800 amp, but, at present, trains do not exceed six cars; diversity between trains is usually experienced, since two seldom begin to accelerate simultaneously in the same section.

Table 1

Variation of Accelerating Current with Loading

Gross car weight	Mean car weight	Average accelerating current per motor	Rate-switch position
lb	lb	amp	
83 470– 94 333	88 900	280	Low
94 333–104 666	99 500	300	Medium
104 666–115 000	109 800	320	High

(2.5) Canadian Differences

In several respects, details of these cars differ from usual British practice, the most obvious being the interchange of the driver's master controller and brake controller. In the cars under review these are operated by his left and right hands respectively. The 96 door interlocks in an 8-car train feed through individual car relays—as in London—but these in turn control, through a master relay, the supply to the controller, thus making it impossible for a driver unintentionally to start the train with any door not fully closed. As opposed to British custom, the starting signal to the driver is visual, not aural, and the provision of "zone" circuits (described in Section 7.2) permits the addition of extra guards who divide amongst themselves the control of the doors. Additionally, guards have independent control of doors ahead and behind their positions. Independent signalling circuits forward for guards by buzzer and rearward by bell from the driver are provided. As will be described later, more than twice as much passenger heating is provided than would be normal in Great Britain; it is supplied in the form of circulated warm air under thermostatic control, with the additional facility of introducing fresh air under slight pressure in the summer.

(3) TRACTION EQUIPMENT

(3.1) Main Power Circuits

The essentials of the main power circuit are shown in Fig. 5, from which it can be seen that the well-known series-parallel grouping of four traction motors is employed, using bridge transition. The two motors in the same bogie are permanently connected in series, their fields being weakened in two stages by non-inductive diverting resistors. Acceleration is automatic and at any one of three rates selected by the driver; his controller gives him the choice of two economical running notches. In the "off" position there is no loop circuit through the four motors, and so there is no possibility of current circulation (spurious dynamic braking) or wheel locking in the event of a car being towed.

(3.2) Traction Motors

Four traction motors are fitted to each car, so that every axle throughout the train is motored; they are frame-mounted in the bogie on resilient rubber bushes shunted with flexible copper braids to bond the motor frames to running-rail potential. The drive is through cardan shafts to gearboxes, the gear ratio being 7·43 : 1; with a new-wheel diameter of 30 in this results in a motor speed of 831 r.p.m. at 10 m.p.h. The motors are rated on 65% field strength, but are designed to operate at 50% if required; at present the minimum setting is 52%. Self-induced ventilation is used to cool the machines, the characteristics of which are shown in Fig. 6.

The conventional long cables out of the motors have been replaced by quickly detachable connecting posts, since these simplify the removal of the motors for periodic maintenance. Two pairs of insulated metal posts are pressed into the motor carcass, the internal leads being bolted to their inner ends. Outside the motor the ends of the posts are bare, tapered and silver-plated. Loose external cables are provided, carrying brass sockets tapered to fit the posts; these sockets are embedded in oil-resisting rubber sheaths vulcanized to the rubber insulation of the cable. Pairs of these sockets are held in firm contact with the posts by strongbacks pulled down by screwed studs. The general construction of the motors is conventional, with four brush arms, roller bearings and skewed slots to reduce noise.

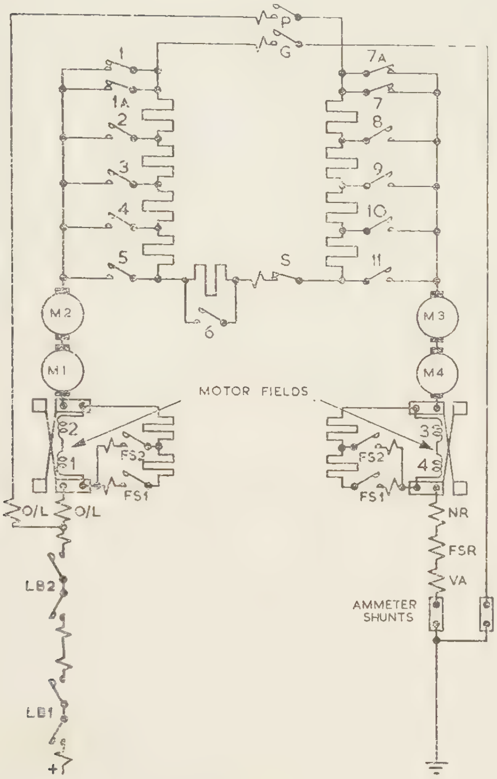

Fig. 5.—Power schematic.

1, 1A, 2, 3, etc. Resistance contactors.
P, G. Parallel grouping contactors.
S. Series grouping contactors.
FS1, 2, 3, 4. Field shunting (diverting) contactors.
O/L. Overload relays.
NR. Notching relay.
FSR. Field-shunting relay.
VA. Volt-ampere relay.
LB1, 2. Line breakers.

Sequence Table

	Step	P.C.POS	LB1/LB2	P	S	G	1 and 1A	2	3	4	5	6	7 and 7A	8	9	10	11	FS1	FS2
Series	Off	1			●		●						●						
	1	1	●		●		●						●						
	2	2	●		●		●					●	●						
	3	3	●		●			●				●	●	●					
	4	4	●		●			●	●			●		●					
	5	5	●		●				●			●		●	●				
	6	6	●		●				●	●		●			●				
	7	7	●		●					●		●			●	●			
	8	8	●		●					●	●	●				●			
	9	9	●		●						●	●				●	●		
	10	10	●		●						●	●					●		
	T	10	●	●	●	●					●	●					●		
Parallel	10	10	●	●		●					●	●					●		
	11	9	●	●		●					●	●				●	●		
	12	8	●	●		●				●	●	●				●			
	13	7	●	●		●				●		●			●	●			
	14	6	●	●		●			●	●		●			●				
	15	5	●	●		●			●			●		●	●				
	16	4	●	●		●		●	●			●		●					
	17	3	●	●		●		●				●	●	●					
	18	2	●	●		●	●					●	●						
	19	1	●	●		●	●						●						
WF	20	1	●	●		●	●						●					●	
	21	1	●	●		●	●						●					●	●

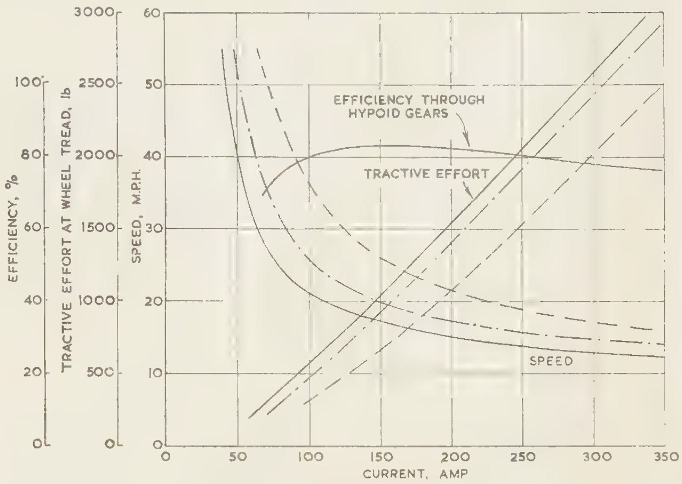

Fig. 6.—Characteristics of traction motors.

	1-hour	*Continuous*
Temperature rise by resistance	120° C	120° C
Power output	68 h.p.	56 h.p.
Current	212 amp	177 amp
Voltage	275 volts	275 volts
Field	65%	65%

——— Full field.
— · — · — Intermediate field, 77%.
— — — — Weak field, 52%.

Gear ratio = 7·43; armature r.p.m. = m.p.h. × 83·1.

(3.3) Transmission

Unlike the majority of electric trains, the transmission of power from the traction motors is not through spur gearing. Since the motors are frame-mounted, provision has been made for relative movement between axles and motors; since the axes of the motors are parallel to the rails, the transmission units also include right-angle drives. Power from a motor is transmitted to a gearbox through a cardan shaft having rubber universal joints at each end; an axially sliding joint is built into one end of the shaft. These provisions enable the shaft to accommodate angular, lateral and longitudinal relative movement between the axle and the motor. On each axle is pressed a right-angle-drive gearbox built on a hub stiff enough to permit sufficient interference between it and the axle to transmit motor torque without resorting to keys. Fig. 7 shows the general arrangement of the transmission, including the provision for absorbing torque reaction. The box is fabricated from steel plate by welding, and contains a single-reduction hypoid-gear unit having a tooth ratio of 52 : 7, the gear dimensions being determined largely by the necessity for passing the unit over the axle. Oil lubrication is employed, taking advantage of the natural pumping tendencies of the rotating teeth; an uncommon feature is that, in place of the usual dip-stick for checking the level of the lubricant, there is a substantial aperture with a skirt or shroud around its cap, so that there is no possibility of dirt or foreign matter accidentally entering the box when the oil is being replenished.

Important advantages result from the use of this method of power transmission apart from those benefiting the car as a whole and mentioned in Section 2.2. Hypoid, bevel or worm gears make it easier to obtain high gear-ratios with adequate ground clearance when small wheel-diameters are used; this simplifies the application of high-speed traction motors, which are lighter and smaller than axle-suspended machines. The right-angle drive permits an uncomplicated method of frame mounting, so that the motors experience smaller impacts at rail crossings, with consequent improvement in commutation and reduced rate of wear of both brush-gear and bearings. The elimination of the

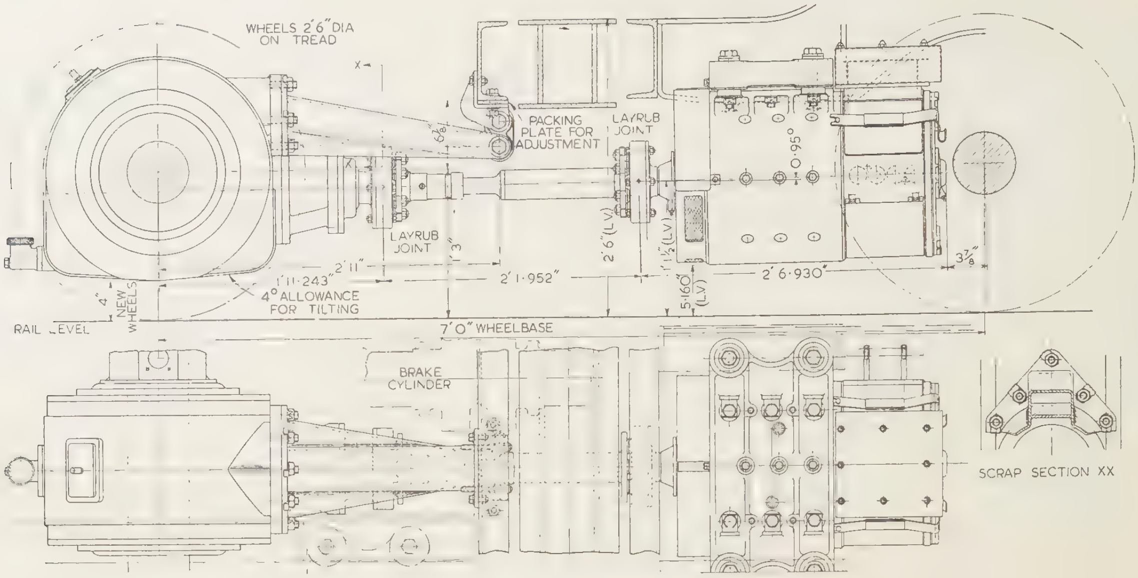

Fig. 7.—Plan and elevation of the transmission unit.

nose and axle suspension brackets has made practical a circular motor frame, which cheapens the cost of machining and of providing jigs and fixtures. Possibly the axle-suspended motor is reaching the limit of its development for urban traction, and the extension of the right-angle-drive layout from streetcars to railways may be helpful in meeting competition from road transport.

(3.4) Traction Control Gear

All major items of traction control-gear are electro-pneumatically operated and are housed in a single equipment case mounted beneath the underframe of the car. Since this case contains the line breakers, the resistance camshaft group, the series-parallel grouping switch, the weak-field contactors, relays, field diverting resistors and is internally wired and piped, the external connections reduce to ten cables and one air-pipe. Several advantages have resulted from this arrangement. Firstly, the layout is very compact, which permits the inclusion of 18 steps from "start" to "full parallel," and also greatly alleviates the problem of accommodating apparatus in the limited space beneath a car already carrying much air ducting. The number of steps in the starting sequence has ensured smooth acceleration, while the closeness with which the average tractive effort approaches the peak permits raising the rate of acceleration to as high a value as is practical without initiating wheel-slip. Secondly, the use of a camshaft has eliminated most of the otherwise usual progression interlocks, reduced the amount of maintenance required and also enhanced the inherent reliability of this scheme. Thirdly, there is an advantage derived from the use of automatic acceleration with an individual current relay in each car which is sometimes not appreciated: there is thereby obtained inherent compensation for variations in traction-motor characteristic and in tyre diameter, which is a valuable asset while accelerating on the flat part of the motor curve.

Two items within the main equipment case are sufficiently unusual to call for comment. The starting resistance is cut out of circuit in stages by a group of cam-operated contactors, the camshaft being driven by rack-and-pinion gearing under the influence of two opposed pistons; one responds to air pressure, the other to oil pressure, and both are controlled by one magnetically-operated valve. The unusual feature is that the camshaft is moved in one direction of rotation when the motors are grouped in series and in the other direction when in parallel. Not only does this help in effecting a quick transition from series to parallel connection, but also, since the "full parallel" position is the same as the "start" position, the trains are rapidly restarted. Even more important is that, when a gap in the conductor rail drops out the line breaker and grouping switch under the influence of the volt-ampere relay, all resistance is already inserted into the circuit before the traction motors are connected to the line when rail continuity is restored. This minimizes the period during which there is no tractive effort and reconnects the motors speedily without risk of flashover or mechanical shock to the transmission. The second noteworthy component is the grouping switch—often called the transfer switch—which reconnects the circuit to effect the change from series to parallel grouping. This takes the form of three contactor elements operated simultaneously by one air engine, which moves vertically a set of ramps or inclined cams mounted on a contact plate. In series grouping the outer pair of contacts is open and the inner contact is closed; for parallel grouping, air is admitted to the engine so that the ramps force the contacts to reverse their positions. Clearly there is no need for interlock contacts or for mechanical attachments to prove that both sets of contacts do not remain closed together.

(3.5) Master Controller

Much of the master controller follows well-known practice, but two features are believed to be uncommon. Basically it has a rotatable handle with "dead man" device and a removable reverse key; it is not combined with the brake controller. The choice of accelerating rate has been removed to a separate drum. No provision is made for operating in full field, and automatic diversion of the motor fields occurs after full parallel has been reached. The layout is unusual in railway work in that the controller is operated with the left hand. The first uncommon feature is that its total height over the (depressed) handle has been reduced to 12½ in, with plan dimensions of 16 in × 18 in; excluding the handle, the controller is only 7 in high. This helped in accommodating equipment in the driver's cab by making it possible for him to sit nearer the controller with his knees underneath it. The second is that a safe method has been

olved of nullifying the "dead man" feature, thus permitting ivers to relieve their arms of the strain of holding the handle pressed while the brakes are applied. This has been achieved fitting a pilot cut-off valve to the controller so that, whenever ere is an application of the electro-pneumatic brake in excess a predetermined value, the "dead man" pilot valve is in-erative. So that an emergency application via the "dead man" vice is not self-cancelling, the cut-off air feed is not taken direct om the brake cylinders or from parts to which air would be mitted by an automatic (emergency) application. It is believed at this feature has never been used in Britain, but it has been ed with success for 30 years in Canada, where it is popular th the train crews and no disadvantages have been found.

Trains are under multiple-unit control from any end driving sition, the leading cab obviously being used except in emer-ncies. To ensure that a train is operated only from one position, e driver is provided with a removable control switch-key, pped in the "on" position. The same key is used to operate equipment cut-out switch.

(3.6) Resistors

The main starting resistor differs from many others in that it mprises a number of units, each made from a single jointless ip of aluminium-chromium–steel alloy wound edgewise and pported on ceramic insulators. The high resistivity of the ip permits the use of thick, and therefore rigid, sections. The ld-diverting resistors are made from copper–nickel-alloy strip ounted on two Micanite-insulated rods; porcelain bushes ovide ample creepage insulation. Permanent resistors for otor-generators and air compressors are similar to the latter t are lighter. The resistors are rustless and have a negligible nperature-resistance coefficient. Terminal tapes for the main sistors are welded to the ends of the strip; copper tapping ips are electrically brazed to the grids in the field-diverting sistors to take out the connections to terminals. The method construction economizes in weight and includes tertiary ulation.

(4) POWER SYSTEM

(4.1) Track Supply

The track supply is derived from five substations, some parated by 6 500 ft and fed by distribution mains at 13·2 kV and c/s. Substations contain pairs of 6-phase mercury-arc rectifiers give the effect of 12-phase operation; each is rated at $1\frac{1}{4}$ MW, bstations being rated at 5 or $2\frac{1}{2}$ MW. Rectifiers are rated in cordance with the American I.E.E. Specification C34.1 ass III, Railway Service, which permits 300% overload for in. All except the one at Davisville also supply nearby eetcar or trolleybus systems, the subway representing about f the total load.

Only one of the two running rails (100 lb/yd copper 0·785 in^2 uivalent) is used for return of traction current, the other rail ng reserved for signalling circuits. Except at special work, ls are Thermit welded, in order to eliminate bonded joints; longer feeder sections are reinforced by connecting a copper gative feeder (1·18 in^2) in parallel with the rail, the two ng bonded together at about 400 ft intervals in the covered, 800 ft in the open-cut, sections. Because substations are uated at sectionalizing points and the track sections are fed m both ends under normal conditions, the total amount of gative feeders required is small. The greater conductivity of contact rail (150 lb/yd, 1·96 in^2 copper equivalent) made sitive paralleling feeders unnecessary. The substations rmally are remotely controlled from a central point through ervisory equipment; alarm boxes at 500–800 ft spacing can be used to cut off power in an emergency from any section of the track, and are telephonically linked with the control room. The system is designated as nominally 600 volts and the substations have been designed to give 570 volts at the busbars at their continuous ratings. However, all the contact rail is normally tied together electrically, and therefore to promote load sharing —and in some cases to compensate for heavy surface-transport loads—the transformer primary taps at some stations are used to lower the direct busbar voltage in $2\frac{1}{2}$% steps to a minimum of approximately 540 volts. The designed performance of equip-ment on the trains was based upon an average supply of 550 volts.

(4.2) Current Collection and Return

Each bogie carries two collector shoes, one on each side, sliding on the top of the positive conductor rail; shoes on the same car are connected in parallel without separate shoe fuses. No positive bus-line is carried through the train, since every car has a full set of traction motors and collector gear. There is therefore no fear of a train stalling at a conductor-rail gap on the main tracks. Omission of the bus-line avoids having to pass 600-volt circuits through the couplers and eliminates a problem of fuse co-ordination. The 600-volt return circuits on the car are, without exception, fully insulated from earth and connected to an insulated negative bus-line individual to each car. Each axle carries a bronze slip-ring housed in an extension of the gearbox; bronze-graphite brushes in insulated holders lead the current from the negative bus-line to the axle slip-rings and thence to the running rails. Precautions have been taken to ensure that the inevitable oil leakage from the gears does not gum the brushes in their holders, although brushes such as these, which contain a high proportion of metal, benefit from moderate lubrication. The negative line is connected in parallel with the four brushes in a car, and because the circuits leading to the brushes are insulated, it is normally impossible for power current to pass through the roller axle-box bearings to their detriment. Provision is made for returning fault currents to the rails by ensuring that there is an adequate metallic path in the vicinity of the king-pins. The low-voltage circuit has its positive terminal earthed, to minimize the possibility of corrosion of fine-wire coils where fitted. Since this circuit is complete within a train, earth return is employed for all the 50-volt apparatus except the electro-pneumatic brake system, which has a wire return. In addition to the numerous fortuitous return paths available, each pair of semi-permanent couplers is bridged by a bare flexible earth-continuity cable; in the automatic couplers, certain contacts are connected in parallel and earthed at the nearest cab connection-box.

(4.3) Current Distribution and Fusing

A main positive 600-volt fuse is not fitted in these trains; in each car, the supply from the parallel-connected shoes passes through a hand-operated isolating switch provided for depot use in conjunction with a test plug and then splits through h.r.c. cartridge fuses to feed the various circuits other than that carrying main traction current. The supply to the traction equipment, because of its magnitude, is taken through a copper ribbon fuse. Cartridge fuses above 60-amp rating are of the lug type; others have ferrules. Similar fuses are used for 50-volt circuits, and all are coloured in accordance with the provisions of the American National Electric Code (C.S.A. Specification C22.2, No. 59). The choice of type and location of fuses is sometimes a contentious matter, and therefore it may be of interest to note that the above-mentioned type was selected because of the ease of replacement and also to discourage tampering with the current rating. Although common in North

America, the latest British underground practice was accepted in respect to shoe fuses, which were omitted, largely because co-ordination is virtually impossible. Any one shoe and its fuse must be capable of carrying the peak accelerating current; hence under normal conditions with two shoes in contact with the rail, the combined fuse rating is twice as much as that of a single fuse. There is then a dead zone of current in which the fuses will not melt, while with higher currents considerable energy is liberated; the resulting arc can be very destructive. Experience elsewhere had shown that faults before the equipment fuses could safely be left to the substation high-speed circuit-breakers, particularly since these so often are arranged for quick tripping in response to a rapid rate of rise of current.

(5) AUXILIARY EQUIPMENT

(5.1) Low-Voltage Supplies

A low-voltage auxiliary supply is provided from a motor-generator at a nominal 50 volts; a lead-acid battery floats across the terminals of the generator and a carbon-pile resistor adjusts the generator field to obtain the desired output-voltage characteristic. One set of apparatus supplies both cars of a 2-car unit.

The motor-generator has two armatures and commutators on a single shaft. Special attention was paid at the design stage to the future problem of stocking spare parts; to this end the two cores, commutators, brush-gear and brushes are interchangeable, with the exception that the motor-type commutator segments have to be reslotted to accommodate the heavier generator windings. The motor has only series excitation, and in the interests of stability while passing conductor rail gaps, is without shunt or separate speed-limiting windings. Its speed on light load is limited by fans at both ends of the shaft; on rise of machine speed, their rapidly increasing power absorption effectively prevents dangerous speeds being attained. The rated output of the set is 4kW at 50volts at any input voltage between 450 and 600 volts; a permanent resistor of 1·2 ohms is in series with the motor.

The lead-acid battery has a capacity of 96Ah at the 5-hour rate and is capable of carrying all the control and emergency loads for three hours at a temperature of 0° C. The battery box may be partially withdrawn from the car without disconnecting its cables, thus simplifying inspection and maintenance.

The voltage regulator is of the carbon-pile type with a minimum of levers; a saucer-shaped star spring balances the pull of the controlling electromagnet and, by varying the resistance of the pile, maintains the generator voltage almost constant. Inherently, a control of $\pm\frac{1}{2}$ volt can be obtained in the neighbourhood of its nominal setting of 50 volts, but a decompounding coil is included which, by augmenting the droop of its characteristic, effectively limits the maximum overload current from the generator into a discharged battery. The present setting is 52½ volts at no load. The regulator can also hold the voltage at 35 volts so that equipment can be tested for reliable operation at low voltage; in addition, it can regulate at 60 volts, which enables the battery to receive an occasional gassing charge direct from its own generator and without removing it to a charging bench. The regulator incorporates an anti-hunting transformer for stability under transient conditions.

(5.2) Heating and Ventilation

Ample heating has been provided in each car, 30 kW being necessary to maintain a reasonable average temperature of 60° F (15° C) inside while the ambient air temperature outside is 10° F (−12° C). The three large doors on each side also inevitably allow much warmth to escape at stations, but on the other hand, an appreciable amount of heat is supplied by the passengers themselves during periods of peak loading. rated voltage the heating capacity built in provides abo 7 watts/ft^3 of interior volume; this may be compared with t 2–3½ watts/ft^3 commonly found in Britain or the 4½ watts/ recommended in France. If this seems generous by Briti standards, it must be remembered that the Canadian winter cold. Each driver's cab has an optional and additional 2k of heating and a small demisting fan to keep the window cle and the cab well ventilated. The coach system comprises pair of fans in each car mounted on a single motor supplied 50 volts; the fans draw air over three banks of resistors ea dissipating 10kW at the rated voltage of 550volts. For safet these were designed for 14½kW at 660volts to ensure that th did not overheat during periods when the track voltage w high. The air reaching the heaters can be either fresh air fro outside or warm air recirculated from inside the car; filters we considered unnecessary and are not fitted. A damper flap mov by a small pneumatic cylinder and magnet valve controls t admission of fresh air into the recirculating system; the tot fan delivery to the car is approximately 2 000ft^3/min and reach the passenger space through grilles built into the seat rise Three groups of thermostats control contactors energizing t three banks of heating resistors; another thermostat contro the damper; lock-out protection is provided against exce temperature in the heater chamber and is duplicated for safet For summer circulation the fans draw in fresh air with the heate de-energized; for winter pre-heating before the cars ent passenger service the damper is kept closed and all air is heat and recirculated. The heater elements are of nickel–chromium iron alloy the resistivity of which is 110 microhm-cm at 20° the temperature coefficient is small and approximately line over the working range, with an average value of 1·2% p 100° C. The motor carrying the fans absorbs about 980 wa at 50 volts and is supplied from the generator side of the batte contactor; such a circuit prevents the relatively heavy load of t two motors in adjacent cars being imposed upon the battery the event of failure of the motor-generator or the track suppl The adoption of 600-volt heater elements and the non-use waste heat from the traction resistors was occasioned primar by the insufficiency of the latter source alone. Some 600-vo heating would therefore have been inescapable and the ductin which even with the present arrangement was very difficult accommodate, would have been too tortuous and wasteful undercar space; simplicity prevailed.

(5.3) Lighting

The bulk of the interior lighting is energized from the 600-vo track supply; neither a 50-volt supply nor fluorescent lighti was selected because, not only would so doing have increas the cost of installation and maintenance, but also the size the motor generator would have had to be increased—entailin in turn, problems of weight, accommodation and capital inve ment. Additionally, in the case of fluorescent lighting, "finge starting was feared at low temperatures. Within the car body t arrangement comprises two rows of fixtures totalling 47 lamp of which six are battery fed and normally energized, providi both regular and emergency lighting; 41 lamps are supplied 600 volts. All these lamps are identical, interchangeable a rated at 48 watts at 30 volts. The battery-fed section compris three paralleled groups each containing two lamps in series; t track-fed circuits comprise 21 lamps in one, and 20 in a secon series string, a resistor replacing the otherwise missing lam With this arrangement an even balance of illumination achieved, giving about 19ft-candles at the reading plane; batte and track-fed lamps have almost equal voltages at the avera values of the two sources of supply, the difference being norma

nperceptible. Other lighting, represented by end-mounted estination and run-number signs, cab lamp, marker and tail mps (and head lamp when fitted), together with miscellaneous dicating lamps, is energized from the battery, with voltage-ropping resistors where necessary. Some lamps are rated at 3 watts at 30 volts, but most are rated at 50 watts at 60 volts. ockets for 600-volt lamps have short-circuiting contacts to store continuity whenever a lamp is removed or fails, and nce adjacent lamps are fed from different circuits, the occasional ilure of a lamp or a fuse will not seriously affect the passengers' mfort.

(5.4) Jumpers and Automatic Coupler Contacts

Semi-permanent jumpers are fitted between cars forming a car unit. Each comprises two 19-core cables permanently tached to the A, or motor-generator, car; the plugs at the ends f these engage with corresponding sockets on the B, or com-ressor, car. Jumper sockets are hinged, face downwards, and e retained in this position by copper shear-pins. This feature revents damage to jumper cables in the event of a 2-car unit eing parted before the jumpers are disengaged in the conven-onal manner. The cars being handed and unsuitable for turning nd for end, the cores need not be paralleled or bifurcated; hence l 38 wires may be used, although electrically some are paralleled obtain adequate current-carrying capacity. Jumper contacts e rated at 10 amp continuously.

The electrical section of the automatic couplers uniting groups f 2-car units has two banks of 23 contacts; for reasons given bove, this provides a possible maximum of 46 circuits, but, in ct, 30 are used for control and indication, some are paralleled nd earthed for reasons already mentioned and some spares main. Only 50-volt circuits pass through jumpers and tomatic-couplers. The general arrangement of the automatic-upler is shown in Fig. 8.

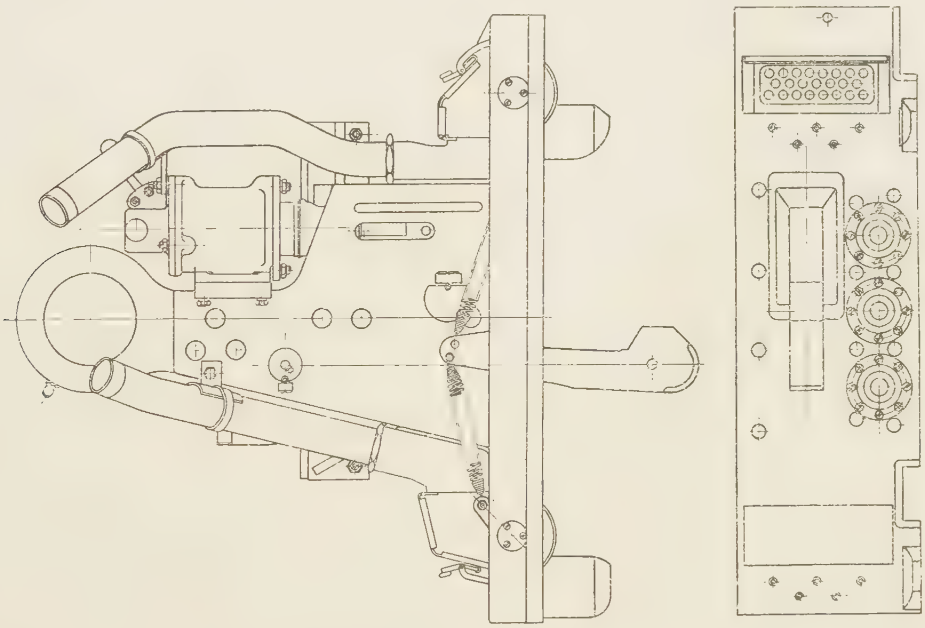

Fig. 8.—The automatic coupler.

(5.5) Low-Pressure Air Supply

As described in the next Section, the main compressed-air pply for braking is derived from reservoirs storing air at a uge pressure of 100–120 lb/in^2. Lower-pressure air is required for the operation of the traction control equipment, the electro-pneumatic doors, the pneumatically moved air-damper in the heating-and-ventilating system and for the windshield wiper. In each car, air for these is obtained from a compact unit supplied through a central filter from the main reservoir pipe-line. The unit incorporates two isolating cocks, pressure reducing valves and pressure gauges, all bracket mounted on a single manifold casting, thus eliminating much pipe work. One half supplies air at 75 lb/in^2 to the traction control equipment and the other half at 65 lb/in^2 to the door apparatus. The isolating cock controlling the latter is ganged to a switch, so that if the cock is closed to isolate all doors in a car the associated interlocking circuits are re-established through by-passing contacts.

(6) BRAKES

(6.1) System and Control

The braking system fitted is that known as the electro-pneumatic (e.p.) self-lapping system with retardation control; it is combined with the well-known automatic Westinghouse brake employing triple valves. A motor-driven compressor mounted on alternate cars supplies air, which is also used for other purposes. The system may be considered as a standard automatic brake on which has been superimposed an instantaneous e.p. control designed to be self-lapping both in application and in release. Upon this arrangement there is in turn superimposed automatic control of the maximum rate of retardation through the movement of two columns of mercury in circular tubes. The e.p. brake is normally used for service stops, the automatic brake being always in reserve. When the e.p. brake is used as the service brake the major advantages of the combination are: simultaneous application irrespective of train length; great flexibility; graduated release; number and frequency of applications limited only by compressor and main reservoir capacity; and the retention of the full brake-pipe pressure in the auxiliary reservoirs, which are therefore always ready for an emergency stop.

The automatic brake is too well known to be described here, but the e.p. brake is less common. It consists of a group of

electromagnetic air valves in each car which are controlled from the driver's cab. During an e.p. brake application air is fed from the main reservoirs, while constant pressure in the brake pipe keeps the auxiliary reservoirs fully charged and the triple valves at their "release" position. An e.p. holding valve is interposed between the release port and atmosphere; an e.p. application valve admits air to the brake cylinders until either the driver's controller laps itself or until a mercury retardation-controller operates. Additionally, a local limiting valve will prevent the brake-cylinder pressure exceeding a preset maximum. Equality of cylinder pressure throughout the train is secured by timing chokes in the various air passages. The relatively heavy currents required to control an 8-car train are not handled directly by the brake-controller contacts or the mercury tubes; to obtain long life, relays are interposed. One of the two mercury retardation-control tubes indirectly interrupts the circuit to the application magnet valves when the retardation reaches a preset value; the other tube de-energizes a separate blowdown valve in each car so as to exhaust air from the cylinders if a higher preset value is exceeded as the train speed decreases. A limit is set to the value to which the pressure can be lowered in this way. The effect is that the two tubes hold the pressure at such a value that the maximum rate of retardation is almost constant, is independent of the length of the train or its average loading and is as high as possible without exceeding the usually accepted limits of adhesion between wheel and rail. Additional to these brake applications initiated by the driver, the guard can in an emergency apply the brakes, using a valve provided on the rear wall of his compartment. An alarm handle, accessible to the passengers, is mechanically linked to the same valve so that, while passengers can initiate an emergency stop by venting the brake pipe, they cannot reclose the valve. Furthermore, automatic trip-arms likewise vent the brake pipe if for any reason the train passes the raised train stop-arm associated with a red signal. When a driver initiates an emergency stop, his brake controller applies both the e.p. and the automatic brake simultaneously. Quick-acting triple valves operate in the well-known manner, but the effect of the electro-pneumatic instantaneous inshot of air to the cylinders before the admission through the triple valves from the auxiliary reservoirs is to raise slightly the brake-cylinder equalizing pressure; hence, when the brakes are applied in this way, the braking force would be higher than if the automatic brake alone were used, but the retardation controller is retained in circuit to avoid wheel-slip at all times.

Brake rigging has for long engaged the attention of both designers and operating staff; it is noisy, inefficient, wasteful of space and requires both inspection and maintenance. Accordingly, it has been eliminated from these trains except for the very small amount required for applying the ratchet-type hand brake; even here, rodding has been avoided. The use of a remarkably simple layout of a single wire cable and a few pulleys has made the hand-brake mechanism virtually noiseless. For service braking each wheel of each bogie has two separate clasp brake shoes, each in turn having its own individual combined brake cylinder and slack adjuster. The brake cylinders incorporate adjustable fulcra enabling the lever-arm ratio to be altered over the range from 5 : 1 to 2·3 : 1, the higher figure being the present setting. This is a useful facility which will assist should future experiments be made with brake blocks having a coefficient of friction substantially higher than that of the present cast-iron ones. Cylinder safety valves are fitted and nominally set at 70lb/in^2.

(6.2) Compressor and Piping

The motor-driven compressor is of orthodox design with two stages of compression; its driving motor is connected to the 600-volt supply through a permanent resistor of 2·38 ohms, a all compressor contactors in a train are linked by a synchronizi wire carried through all jumpers and couplers. Motor co pressors are carried only in alternate cars, occupying the spa otherwise occupied by the motor-generators and batteries. T nominal air pressure is 100–120lb/in^2 in the main reservo and 85lb/in^2 in the brake pipe. Steel piping is used for t continuous main reservoir pipe (more accurately called a reserv equalizing pipe), but the brake pipe and all others carryi filtered air are of copper. Several advantages accrue: troub due to scale and dirt are reduced, the weight is less and pi bending is a little easier.

(7) POWER-OPERATED DOORS

(7.1) Apparatus

The doorways have the familiar double doors, each with separate air engine accommodated beneath a neighbouring sea each door weighs 94lb, but spring protection avoids injury to passenger caught by closing doors. The simple different pressure system is used, the smaller of the two cylinders bei permanently supplied with air at 65lb/in^2. Air at the sar pressure is admitted to or exhausted from a larger (contro cylinder to open or close the door respectively; the operati times are 1½sec to open and 2½sec to close. The air supply the control cylinder passes through an "open" electromagne valve fitted with a pneumatic latch valve so that only momenta energization of the magnet is necessary; this is more reliab than a mechanical retaining latch. Doors are closed by exhaus ing the retaining chamber, thus allowing the "open" valve fall. Door-proving interlocks are operated from the doo themselves and not by the engines, since a false indication mig otherwise be obtained if an operating lever parted from its doo The interlocks consist of tilting mercury switches from whi the usual flexible pigtails have been eliminated; such switch also obviate the intermittent faults previously experienced wi ordinary sliding- or butt-contact interlocks.

In addition to the normal operation of the doors, provisio has been made for emergency egress by passengers and for sta to enter and leave any car. In an emergency the passengers ca operate a safety device acting on the pair of doors nearest t cab on each side of the car. If normal current and air pressu are available, these doors open automatically; if these suppli have failed, the doors are mechanically unlocked, permitting passenger to pull open a door by hand. Access to and from t cars by staff either outside or inside is aided by key-operat electric switches located in inconspicuous places. If normal a and current supplies are not available, entrance and exit for sta is through the end doors above the couplers.

(7.2) Operating Circuits

The door circuits pass through each driver's cab which, wh vacant, can be used as a guard's position if on the platform si of the train. Here are located a key-protected drum switch give electrical access to the door circuits and two sets of "oper and "close" pushbuttons, so that control may be exercis separately over doors ahead and behind the position occupie The guard on duty is not restricted to the trailing cab and may ride in any cab on the correct side of the train. No provisio has been made for local control of the doors by passenge either from within or from without; the predicted density passenger flow is such that it is felt that the best results a obtained by concentrating control of the doors at the guard position. The total number of train wires for door control five at the automatic couplers and seven in the semi-permane jumpers.

Control is effected by momentarily energizing from the 50-volt ystem a door "open" or a door "close" train wire on the platorm side of the train; the act of operating the door-control rum switch when taking possession of a position earths all open" train wires on the other side to avoid any chance of ccidental operation due to stray leakage or fault currents. A uard has independent control of the doors ahead and behind is position. Provision has been made for more than one guard o ride in the train simultaneously if special events should make ivision of responsibility necessary. The zoning feature thus ntroduced is obtained automatically, as the operation of addiional door-control drum switches automatically breaks the ontrol circuit into separate sections, each guard then having omplete control of his section. Because of the safety earthing f the "open" wires on the non-platform side, all guards must ide on the same side. It is not easy to describe succinctly the ircuits whereby zoning is obtained automatically and it is hoped hat Fig. 9 will assist in understanding this feature.

the depot under its own power, even if the whole door-loop circuit becomes faulty.

(8) SAFETY FEATURES

Safety can be considered in this context as having two subdivisions: safety of apparatus and safety of persons, including operation. In addition to conventional precautions, such as adequate fusing and the segregation of the 50-volt and 600-volt circuits, wherever possible the circuits are arranged to fail to safety. For example, the supply to the heater controls and contactors is taken from the associated fan-motor supply so that they cannot be energized until the motor is supplied. The correct functioning of the e.p. brake circuits is continuously displayed to the driver by small indicating lamps in his cab; these vital circuits are also protected against inadvertent operation due to stray leakage current by having their common return circuit insulated from earth, carried in a separate train wire and earthed at one point only by contacts in the driver's control switch. Indicator-lamp failure is construed as equipment failure and the driver proceeds with caution.

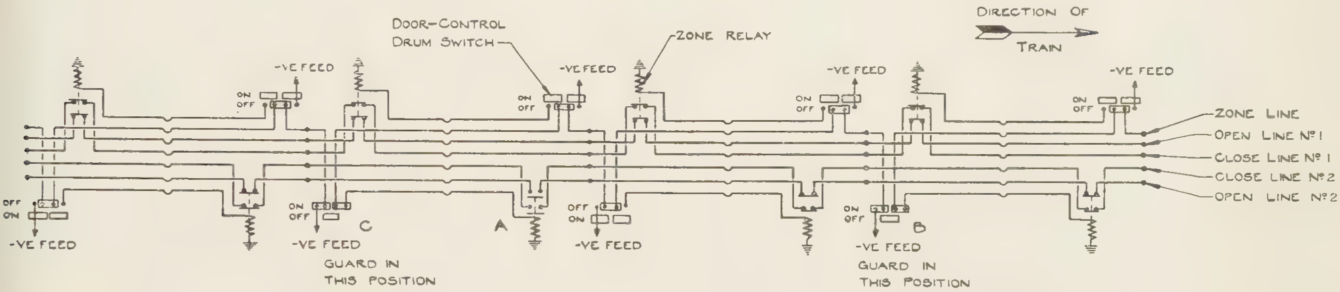

Fig. 9.—Zoning-feature diagram, as applied to an 8-car train with two guards.

Control is distributed equally between guards.
Only wires necessary for zoning are shown.
Relay A is energized through door-control drum switches B and C, in "on" position.

(7.3) Proving and Signalling Circuits

A loop circuit exists in each car through each door interlock witch. When a door is open, this local car loop is broken and a elay in the car is de-energized; one pair of its associated contacts ompletes the feed to "door open" indicating lamps outside the ar, while another pair interrupts a train loop circuit. When all oors are proved shut, the relays establish the train loop carried round the ends of the train by contacts associated with the utomatic couplers and energize a control relay in the driving ar in addition to pilot lamps in all cabs. The guard is able to gnal forward either to the next guard, or to the driver if zoning not in use, by a simple buzzer circuit; in this way each guard an pass forward a signal that his part of the train is ready to start. he driver cannot anticipate the starting signal nor ignore his doors closed" pilot lamps, for the traction control feed passes ver the contacts of the control relay in his car; the relay does ot close and hence power cannot be applied until the door terlock loops are all completed. Present practice, however, is or the guard not to give a buzzer signal but for the driver to art as soon as his pilot lamps show that all doors are shut. he driver can signal back to all guards simultaneously by a mple bell circuit which is exclusive to him and not available any guard.

In the event of the circuits within a car being faulty or a door iling to close completely, the staff can identify the defective ehicle by means of the external "door open" lamps and also n isolate either a single door or a complete car: so doing ridges the associated part of the interlock loop and restores ormal signalling. There is also in the driver's cab a sealed witch which can be used to by-pass the traction control relay entioned earlier. A train can therefore be worked back to

The safety of passengers and of operation is ensured mainly through the automatic signalling and trackside train stops—a subject outside the scope of the paper. Within the train itself provision has been made to prevent it being started if any door is not completely closed or if the air pressure is insufficient to provide a full brake application. For persons on platforms, safety is ensured by pairs of collapsible pantograph gates linking adjacent car ends on each side of the train which eliminate the danger of persons slipping between cars. Safety in motion is enhanced by strong anti-telescoping pillars built into the car ends and extending from about 2ft below the floor to about 1½ft above this level. The body end-framing also serves to protect the passengers in the event of mishap, as it is of box construction and would offer considerable resistance in the event of a collision.

(9) COMPARISONS WITH SIMILAR STOCK

In the comparison of the new Toronto rolling stock with that used elsewhere, suburban systems such as that between Liverpool Street and Shenfield will be disregarded. Modern city stock may be represented in Great Britain by Waterloo and City trains installed in 1940, the deep-level Tube stock on the Bakerloo and Northern lines and the latest Surface stock of the London Transport Executive. Across the Atlantic, the 1952 extension to the Boston system and the new cars in New York are the most recent. All these undertakings operate at approximately the same voltage, i.e. nominally 600–660 volts d.c., and employ conductor rails to feed the trains; Boston, while retaining conductor rails in the existing tunnel sections, uses overhead catenary construction for its eastern extension, the greater

part of which is through filled marsh-land along the sea coast, where delays due to ice accumulations on third rails had been experienced. The reasoning had a premiss different from that which led to the proposal to use overhead contact wire in the interim period of the future Toronto Queen-Street subway where standard P.C.C. streetcars will be used initially.

Data from the above-mentioned systems are set out in Table 2,

Table 2

Comparison of Systems

System	Number of cars per train	Seats	Tare	Installed H.P. 1-hour rating	Installed H.P. Continuous rating	Weight/power ratio 1-hour rating	Weight/power ratio Continuous rating	Initial acceleration	Average run
			lb			lb/h.p.	lb/h.p.	m.p.h./sec	ft
Toronto Subway	8	496	667 760	2 176	1 792	306	372	2·3	2 145
New York (R 10)	8	448	648 000	3 200	2 640	203	246	2·5	3 874
New York (R 12)	8	352	608 000	3 200	2 640	190	230	2·5	2 561
Boston (East Extension)	8	384	379 200	1 760	1 520	216	250	2·3	2 864
L.T.E. aluminum Surface stock	8	320	515 000	1 760	1 280	293	402	2·0	3 400
L.T.E. steel Surface stock	8	320	609 000	1 760	1 280	346	476	2·0	3 400
L.T.E. Tube stock	7	290	396 000	1 680	1 200	236	310	1·45	3 700
Waterloo and City Line	5	236	253 120	760	—	300	—	1·10	7 413

using, wherever possible, 8-car trains as a common denominator. Initially, it had been desired to use weight and power ratios in Toronto approximating to those in Boston and other American cities, but, in fact, the new Canadian subway cars will be seen to follow British trends in these respects. The Boston system shows in its weight/power ratio how closely it has followed P.C.C. streetcar designs, light in weight and intended for short-haul frequent-stopping service. The R10 rolling stock in New York has dimensions somewhat similar to those of the Toronto cars, being 10ft wide and 60ft long, but it is used on an express schedule. The R12 stock operates a local stopping service, but is 9ft wide and 52ft long. Each has a cab at each end and has all axles motored. The remaining systems, whose rolling stock was designed in England, have trains whose median weight/power ratio is approximately 293lb/h.p. The apparently increasing magnitude of this ratio in recent equipments is largely due to better utilization of the traction motors and reduced installed horse-power for a given duty.

Rates of acceleration seem to be stabilizing at 2·3m.p.h./sec for vehicles operating on enclosed tracks and stopping $1\frac{1}{2}$–2 times per mile. Toronto used that rate, being influenced by the widely held view that higher rates are not economically justified, although adhesion would permit them in Toronto and Boston. In passing, the low rate of acceleration of the Waterloo and City system is explained by the relatively long run of 1·404 miles between the only two stations. No continuous rating is shown in the Table for the latter system, as the motors are totally enclosed and such a rating, while not without value, is not comparable with the others quoted for ventilated motors.

Comparing auxiliaries, the trains mentioned as running in Great Britain have low-voltage lighting, no pressure ventilation and only a small amount of internal heating. Those for the United States and Canada use series circuits for lighting and incorporate both ventilating and heating apparatus. The differences are due largely to climatic variations.

(10) ACKNOWLEDGMENTS

The paper is published with the permission of Bepco Canada, Ltd., and the author is also obliged to the Toronto Transit Commission for permission to make extensive references t their system. The paper could not have been written withou the co-operation and help received from the principal sub-con tractors, British Thomson-Houston Co., Ltd., Crompto Parkinson Ltd., Westinghouse Brake and Signal Co., Ltd J. Stone and Co. (Deptford) Ltd., G. D. Peters and Co., Ltd and many others too numerous to detail. Finally, the autho gratefully acknowledges that permission to publish the pape was accorded him by the main contractors, The Gloucest Railway Carriage and Wagon Co. Ltd., with whom the T.T.C had placed the order for these cars.

(11) APPENDIX I: DETAILS OF ROLLING STOCK

Total number of cars	104
Nominal track voltage	600 volts d.c.
Average track voltage	550 volts d.c.
Running rail section (Main track)	100lb/yd
Running rail section (Yards)	85lb/yd
Conductor rail section	150lb/yd
Track gauge	4ft $10\frac{7}{8}$in
Bogie wheel-base	7ft 0in
Bogie centres	38ft 0in
Radius of minimum curve	260ft horizontally
Radius of minimum curve	2 000ft vertically
Width of car body	10ft 4in
Height, rail to roof	12ft 0in
Height, floor to roof	8ft $2\frac{1}{2}$in
Length over anti-climbers	57ft $1\frac{1}{2}$in per car
Length over body	55ft $7\frac{1}{2}$in per car
Doors, height of opening	6ft 4in
Doors, width of each opening	3ft 9in; three per side
Number of seats per car	62
Standing passengers (maximum crush)	207
Weight, tare	83 470lb
Weight, all seats filled	92 150lb
Weight of a traction motor	944lb, less support bracke
Continuous rating of one car	224h.p., 550 volts
One-hour rating of one car	272h.p., 550 volts
Accelerating current (median rate, parallel)	1 200 amp per 2-car unit
Type of gear	Hypoid
Gear ratio	52 : 7
Wheel diameter	30in, new
Minimum clearance to rail	4in, new wheels

Average distance between stations	2 145 ft
Overall length of run	$4\frac{1}{2}$ miles
Number of intermediate stops ..	10
Average schedule speed	$16\frac{1}{2}$ m.p.h.
Average acceleration	2·3 m.p.h./sec.
Average deceleration	2·8 m.p.h./sec
Type of control	Multi-notch, automatic acceleration
Number of notches (series) ..	9
Number of notches (parallel) ..	9
Number of notches (field-weakening)	2
Number of running positions ..	2
Low-voltage supply	Motor-generator and battery
Motor-generator continuous rating	4 kW
Type of battery	Lead-acid
Capacity of battery	96 Ah at 5-hour rate
Nominal system voltage	50 volts
Heating, per car	30 kW maximum at 550 volts
Lighting (main)	Incandescent filament, fed from track
Brakes, type	Electro-pneumatic, self-lapping
Compressor displacement	43 ft^3/min
Compressor maximum pressure ..	140 lb/in^2
Door control	Electro-pneumatic, not passenger controlled

N.B. Trains consist of groups of 2-car units.

DISCUSSION BEFORE THE INSTITUTION, 10TH MARCH, 1955

Mr. A. W. Manser: It is gratifying that British industry should have been given the opportunity of supplying so much of the equipment for this subway installation. Before construction commenced, the responsible authorities in Toronto surveyed urban practice over most of the world; they visited London Transport and have incorporated in their system quite a number of features which are current practice with us.

Table 2 indicates that the initial acceleration of the Toronto stock is 2·3 m.p.h./sec; however, the Toronto stock as ultimately produced was somewhat heavier than originally contemplated, and I should like to know whether this figure is actually achieved, or whether it is simply that which was originally intended. The results of some of the early tests carried out in Toronto show that the motor temperatures are surprisingly low and prompt the query as to whether they are working up to this acceleration of 2·3 m.p.h./sec.

A surprising point about the test results is a reference to the blowing out of the traction motors on what appears to be a monthly basis. This is something which we on London Transport would not like to have to contemplate, and certainly not to do. Are the Toronto engineers really doing this periodic blowing out at such a short interval?

On the question of temperature rise, I am surprised to note that in the test results I saw the largest rise appears to be on the gear-case.

Section 7.2 refers to the zoning feature whereby additional guards may be employed on the train. The experience on London Transport is that it is precisely this sort of provision which results in unexpected difficulties, and we feel that the simpler the door circuits can be kept the better. At one time we had provision for two guards on a train, but the troubles which arose were manifold and very difficult to cure. Have any door-circuit troubles emerged so far in Toronto?

I notice that shoe fuses have been omitted from the Toronto stock. They have also been omitted on the later types of stock on London Transport as being more nuisance than value.

I should like to know what the experience has been so far with the relatively high-speed traction motors. Experience over a considerable period is necessary, because with these high-speed machines it is likely that for the first year of their life they will run satisfactorily, and it is only when the commutator begins to deteriorate that commutation troubles are likely to arise.

I was surprised to note the relatively large voltage drop which occurs in some places on the system. Voltages down to 460 volts on the rolling stock are mentioned; this is surprising in view of the fact that 150 lb conductor rail and reasonably close substation spacing are used.

The analogy between the original London tube between King William Street and Stockwell and the Toronto subway brings up a point on which the Toronto authorities have not found it possible to follow the advice which we gave them. The original tube from Stockwell to King William Street crossed the Thames to the west of London Bridge and then turned abruptly to the right under Arthur Street, terminating under what is now Adelaide House, at right angles to London Bridge. It was to a great extent the inclusion of a very sharp curve adjacent to King William Street Station that necessitated the abandonment of that part of the line at a later date and led to the necessity to go back almost to the Borough station and drive fresh tunnels all the way, crossing the river to the east of London Bridge and passing under the old King William Street station. I hope that the Toronto authorities, having been unable to follow our advice about the paramount necessity to avoid sharp curves, will not eventually be obliged to go to similar expense to eliminate the nasty curve at the south end of the line between Union Street and King Street.

Mr. H. H. C. Barton: Much credit is due to the officers of the T.T.C. for specifying such a suitable train for their service before they had experience of subway operation. From the figures given it follows that only four 2-car units are available for maintenance and traffic spares during peak periods; this service intensity must surely equal the best in the world.

The staff who operate these trains are basically P.C.C. streetcar staff, a fact which has influenced some design details. I question whether it is good practice to link the door interlock and control circuits. While this feature ensures that the train cannot start until the last door has closed, it may introduce danger if the driver tries to start prematurely under a safe lookout condition, because this condition could become an unsafe one during the interval before the last door has closed. I have in mind danger to staff crossing tracks at stations. Furthermore, interlocks can open-circuit; even overcrowding in doorways can cause this. Drivers might be in difficulty if this happened while ascending grades under power. I think drivers should be given unfettered control except for the passenger-operated emergency brake. Experience will show, however, whether this feature is good or bad; it is cheap and easy to fit, and cheaper and easier to remove, by merely shunting the relay.

The author praises the hypoid gear for this service. This gear returns unsprung weight to the axle, although it enables small

high-speed motors to be located on the trucks. High-speed motors, however, are susceptible to design difficulties if mechanical margins are to be preserved. These drives seem to have advantages when high-performance cars must be designed for narrow-gauge railways, because their use would enable the traction motors to be suspended from the underframe. Time will show whether the right-angled drive is better for subway service than the all-sprung gearing used extensively in Chicago and New York and, more recently, in Stockholm.

London Transport undertook extensive service tests on the new design of door interlock used on these cars. A well-conducted service test is the only way to obtain a worth-while answer in a reasonable time, particularly with door equipment. The statisticians tell us that 40 of London's power-operated train doors open and close with every heart beat; I cannot vouch for this, but it certainly describes the conditions which door equipment must satisfy.

Mr. F. W. Sinclair: The Toronto cars ride exceedingly smoothly and the noise level is very low indeed. Even at speeds approaching 50 m.p.h., the cars rode well when on test on continuously-welded track. We thought that this was an achievement, because, of necessity, the springing was rather harsh in order to maintain a suitable height of car exit at platforms under heavy crush-loading conditions.

We built 100 steel cars and six aluminium ones; the whole of the superstructure of the latter comprising the body frame panelling and the underframe is of aluminium alloy. The saving in weight over the steel car is about $5\frac{1}{2}$ tons. The power bogies and the underframe bolsters of the aluminium cars, however, were of steel. Extrusions were used where this type of construction is beneficial, such as for the cant rail and pillar sections. The exterior aluminium panelling was left in the unpainted condition after being surface finished. The welding of the panel joints and any others was effected by the argon-arc process, and the colour matching was so good that the joints could scarcely be seen by the naked eye after the finishing process. The rivets also were virtually indistinguishable.

The aluminium cars on test were loaded with 15 tons of ballast, and, in spite of the low modulus of aluminium alloys, the deflection at the middle of the cars under this load was barely $\frac{3}{16}$ in; we think that this was due to the effective design of the body sides, in spite of the position of the doorways, which were required to be in what, from a structural point of view, were rather awkward positions, presumably to suit traffic flow.

The heating and ventilating systems of both the steel and the aluminium cars, comprising 30 kW of heating under "cascade" control, was of a very interesting design, developed for use in the cold winters and warm summers experienced in Canada. Virtually the whole of the air space in the body sides was required for recirculating air ducting, which had to be suitably insulated. Unfortunately this equipment, with its ducting, weighed more than 30 cwt, thus adding to the weight of the car.

The energy consumption of the aluminium cars was found to be directly proportional to the saving in weight, i.e. 12% lower than that of the steel cars.

A further interesting feature to which the author refers is the transmission (Fig. 7). The propeller shaft has rubber couplings, and twelve months of service have shown this arrangement to be very successful. A relatively small angle of movement of the propeller shaft in the vertical plane, say 2° maximum each side of the centre line, is preferred for an application of this kind, to ensure long life of the rubbers, and this we were able easily to maintain by using the particular type of torque-arm arrangement shown in Fig. 7.

I believe that high gear-case temperatures in hypoid gears with the chosen ratios are common; I raised the question with the makers, who were not alarmed. This hypoid is pressed on to the axle, on a sleeve, whereas in the P.C.C. standard axle arrangement in common use on tramways in North America the crown wheels are mounted directly on the axle and the pinion is housed separately in a cannon-type casting. By that means it is possible for the pinion to push the crown wheel away from the axle if the axle should deflect sufficiently when the drive is on; this is a well-known feature of the gear, but it throws considerable strain on the thrust races. The races are very large for that reason and in the early days I believe some failed in service.

The aggregate mileage of fifty 2-car units up to the end of 1954 is approximately 2 500 000 miles, and, since the railway was not opened until the end of March last year, it will be realized that the cars have been running for about nine months.

Mr. Frederick W. Roberts: I propose to confine my remarks mainly to the control equipment. The paper gives particulars of three rates of initial acceleration which the driver can use. I think that the driver will probably choose the maximum rate to keep up his schedule, but I should be interested to know the percentage peak adhesion figures for, say, a tare weight unit, on all three rates and whether these figures include effect of weight transfer.

With regard to the traction power circuits, the author states that there is no possibility of getting current circulation or wheel locking. Here I should like to refer to Fig. 5. Apparently these cars have been running for some time, but if there is flash-over or earth fault on, say, the brushgear or armature of motor No. 3, there will be circulating currents, depending on the direction of motion. Another point is that motors Nos. 1 and 2 have their field windings on the positive side, the line side, of the armatures. If a flashover occurs on the positive side of No. 1 motor armature those fields will in effect be across the line and there would be a very heavy current; this would set up a braking effect which might have some serious results on the transmission.

It appears that tertiary insulation has been provided for the main resistor. Are there any special reasons for this, because it seems to err very much on the liberal side?

I should like to know whether the collector gear is of the gravity type, what the shoe material is, and what sort of life is obtained from the shoes.

In Section 4.3 it is stated that the power traction supply of the vehicle is taken through a copper ribbon fuse. Is a fuse really necessary? Surely the line circuit-breakers, in conjunction with an overload relay, should be able to deal with faults.

The large size of the battery is striking, in view of the fact that it is required only for emergency operations. The risk of failure of a motor-generator set should be almost nil. While I am sure that the battery size has been chosen for the duty specified, I feel that the duty required is heavier than an emergency battery should be called on to provide.

The coach-heating arrangements surprise me, because while the heating elements are fed from the line, the fans which draw the air over the elements are supplied from the generator of the motor-generator set. If the fan motors are operated on the line voltage, failure of power supply will shut down the fans and unload the heater elements at the same time, but in the scheme adopted here the fan may shut down and the heater elements still be energized. This is no doubt taken care of in the control circuits, but the fan motors represent almost 50% of the rated output of the motor-generator set and would seem to be the main reason why all the motor-generator sets must run all the time that the trains are in service.

I should like the author's comments on why the traction-motor fields have been shunted non-inductively, as opposed to tappings on the field windings.

Mr. J. G. Bruce: It is fairly common knowledge that rapid-transit railway systems in the United States have developed from

ramway systems, and therefore it is not surprising that the oronto system has continued the use of the abnormal gauge of ft $10\frac{7}{8}$ in. It is no longer a satisfactory proposition to run ubway trains in between tramcars, as was done in the early days New York. I do not understand, therefore, why this gauge as been continued for the Toronto subway, now that it is bviously a unit on its own. In view of the need most other ties with subway systems have found to provide extensions over nain-line railways, I wonder whether any attempt has been made the design of the rolling stock to ensure that it could be onverted to run on a gauge of 4 ft $8\frac{1}{2}$ in at some future date. Ias all the space been taken up between the wheels or could they e pushed in a little?

In Section 3.4 reference is made to the arrangement by which ne camshaft was moved in one direction of rotation when the notors are grouped in series and in the other direction when in arallel as unusual. This system was first used in Britain xperimentally in 1936, but a large number of equipments of this ype were operating at that time in New York. London Transort has now more than 1 000 in operation, so that the use of the djective "unusual" is unfortunate.

In Section 4.1 it is noted that one of the running rails is used or signalling circuits while the other is continuous for return of raction current. This system is similar to that used in New York, but some of the sections, I am surprised to find, must have ne return circuit reinforced with a copper conductor. Was onsideration given to using the fourth-rail system, as in London, nce this might have been a cheaper installation and has certain echnical advantages, especially with 40 trains per hour and when oller bearings are used on the rolling stock?

In Section 5.3 it is surprising to find that the main lighting ystem consists of incandescent-filament lamps in series with nort-circuiting caps. This system found much favour with ramways several decades ago, but it seems rather old-fashioned or a new subway system. The decision appears to have been nade on economic grounds, and, in view of this, some figures elating to the savings on this installation would be interesting, specially since a motor-generator set of quite large dimensions already provided.

Another feature of the rolling stock which seems at first sight n unnecessary complication is the small difference in air pressure equired between the control system and the air doors.

I am surprised that the firms installing the equipment did not et together and provide a 65 lb pressure for both systems, nstead of a 60 lb and a 70 lb system.

Mr. F. C. E. Smith: It is suggested in the paper that the axleung motor has possibly reached the limit of its development for rban traction, but I should like to know how far the hypoidear drive can compete with it. For instance, a 2-motor equipent employing conventional nose-suspended motors could be uilt to give almost the same performance as the 4-motor Toronto quipment, and I wonder whether the hypoid drive can be built r this higher power. The efficiency with the hypoid drive ven in Fig. 6 does not exceed about 83%, which compares nfavourably with a spur-gear drive.

It will be noted from Table 2 that London Transport achieve acceleration of 2 m.p.h./sec with 2-motor equipments, and the tra 0·3 m.p.h./sec obtained in Toronto does not justify the pense of the 4-motor equipment. However, since the Toronto aches have every axle motored, dynamic braking could be ost advantageously employed, and it would be interesting to now why this was not done.

The adoption of the top-running conductor rail in Canada ems rather surprising, for the amount of snow and ice countered must be considerably more than in this country. understand, however, that the first trouble with snow is due to clogged points, and the snow then piles up on the track and on the conductor rail during the traffic delay while the points are being cleared. I notice that at Toronto the points at both terminals are under cover, and this may assist a great deal in keeping the trains running and so keeping the conductor rail clear of snow.

I do not follow the author's statement in Section 3.4 that the individual current relay in each car gives compensation for variations in traction-motor characteristic and in tyre diameter. As I understand it, the accelerating relay will have no effect on the performance of any car when it is accelerating on the motor curve.

Mr. B. J. Prigmore: It is interesting to see, from the early part of the paper, the philosophy of the Toronto Transportation Commission. There was a great deal of congestion on the surface and it was decided that it was possible to cope with it only by taking public transport off the surface. That theme is now increasingly being heard in England, and I feel that the New World has been ahead of us in doing something about it. Moreover, it was not primarily a question of tramway replacement: rather was it decided that even a reserved-track tramway could not do the job and that it was necessary to have a full-scale railway.

The general trend in America, I think, is towards all-electric rapid-transit vehicles, certainly for streetcars. Was serious consideration given to all-electric cars for the Toronto subway? On the other hand, it is very encouraging to British manufacturers and designers that so much of British practice was actually adopted.

I am intrigued by the phenomenally high rotational speeds of the motors when the trains are running free. Is the referred inertia of those motors significantly greater than if there had been four motors of somewhat lower speed on the same cars? If it is, a little of the energy consumption is a function of using motors of such a very high rotational speed.

Mr. C. M. Cock: It is evident that those responsible for the planning of the Toronto subway had much foresight, inasmuch as they have planned to the maximum extent with regard to the movement of traffic. The system is designed for an ultimate capacity of 53 000 passengers per hour, and signals for a headway of 40 trains per hour. I believe there are certain lines on London Transport that are signalled for 40 trains per hour, a theoretical maximum, but I am not sure whether 40 trains per hour actually have been, or can be, run. No doubt the authorities have observed that Toronto, like several other Canadian cities, is growing like a mushroom.

From other aspects, however, the planning appears to be not so good. Two speakers have referred to the conductor rail, one in regard to the voltage drop and the other in regard to the effect of climate. In view of the future growth of Toronto, one would expect this line to be extended eventually for several miles into the country. With good transport, the population will move out to the country and the line will move with them, or perhaps before them in anticipation of building development. A 600-volt conductor rail is not ideal in these circumstances. Moreover, in view of the amount of open line on this so-called subway, I feel that with the very severe cold weather conditions in Canada there may be risk of interruptions to traffic by freezing on the top-running conductor rail.

From Fig. 7 the hypoid gear seems almost as large as the traction motor, but size may not be related to weight. How much weight is relieved from the axle as compared with a conventional axle-hung motor?

It is stated in Section 3.3 that the advantages of the hypoid gear is simplification of the high-speed traction motors, which are lighter and smaller than the axle-suspended motors. This is a little difficult to understand. The latest motors on the British Railways Southern Region suburban stock, for instance, are

17·8 lb/h.p. including gears, whereas these Toronto motors are 13·8 lb/h.p. without the transmission system. I imagine that if the weight of this system were included, the Toronto motors might be heavier per horse-power than those of the Southern Region. Some further explanation is needed.

It is also stated that the axle-suspended motor is reaching the end of its development. I should like to have more evidence and reasons for this alarming statement.

The very high rate of acceleration of 2·3 m.p.h./sec has been adopted on the Toronto system. Comparing the total running time, including stops, with that obtained with an acceleration of, say, 1 m.p.h./sec, I should like to know whether the saving in time is really worth the additional expense of higher-horse-power motors and greater installed capacity at the substations to meet this demand. There may or may not be a saving in the watt-hour consumption per train-mile compared with a system using the lower rate of acceleration, and information on these points would be very interesting. A figure of 5·75 kWh/car-mile has been given, but this is of no value, because cars can vary in weight very greatly; what I want to know is the energy consumption per ton-mile, which is usually expressed in watt-hours.

These modern subway cars are comparatively heavy, as shown in the following table:

Average Tare Weight per Passenger

	Crush Loading ton	*Seated* ton
British Railways, Southern Region ..	0·151	0·348
British Railways, Liverpool-Southport	0·146	0·338
London Transport light-weight surface stock	0·139	0·665
Toronto	0·218	0·597

The Liverpool–Southport coaches were commissioned in 1939, and it is surprising that modern technique has not saved more weight in the Toronto cars, particularly in view of the savings in energy that can be obtained.

Mr. G. A. Meier (*Switzerland*): In Switzerland we have no subway system, but we are very interested in the subject. We have quite a number of electric cars in Zürich, and three years ago we made some tests with fluorescent lighting directly connected to the line voltage of 600 volts d.c. The tests have proved very successful, and we now have about 20 cars running with 600-volt d.c. fluorescent lighting of the interior, providing increased comfort in the form of good light to passengers and staff and about ten times longer life of the fluorescent tubular lamp as against the old incandescent-filament lamp.

Mr. W. N. Tonkyn: In studying the general arrangement drawings (Fig. 4) I have particularly noted that, at 62, the seating capacity is half as much again as the 40 of a London Transport surface-line car. The latter, admittedly, is shorter and narrower, with an interior area of about 410 ft^2 compared with the Toronto car's 520 ft^2, but scaling-up its seating in proportion to area gives only 50, still 12 short of 62. Further study shows that the Toronto car's additional seating is obtained at the expense of the doorways, a 3 ft 9 in opening having been selected in preference to the 4 ft 6 in one standardized by London Transport, and I should be interested to know whether the doorways have been found adequate for crush-load conditions.

The total door opening in a car side, expressed as a percentage of car-body length, is 20·2% for the Toronto car, whereas it was 25·0% for an experimental outer-suburban car which London Transport built, of similar length but smaller capacity, with three double doorways per side. Current London Transport practice for cars without cabs is to have two double and two single doorways per side, which arrangement, with the shorter car, gives a ratio of 26·4%.

In Section 2.3 a figure of 40 000 passengers per hour is given as the maximum crush loading, presumably for working 8-car trains at a headway of 2 min. This corresponds to an average standing passenger load of 105 per car, as against the 207 maximum shown in the Appendix. It would clearly be impossible to transport 207 standing passengers per car without widening the 2 min headway, but it would be interesting to know how the figure of 40 000 passengers per hour was calculated.

In Section 3.4 the author says that ". . . all resistance is already inserted into the circuit before the traction motors are connected to the line when rail continuity is restored." This can hardly be quoted as a special feature of the camshaft equipment under review; it is a fundamental requirement that rheostatic equipments must provide such protection for the traction motors.

Have the Toronto Transit Commission had any second thoughts on whether the provision of a power bus-line linking the two cars of each unit might not, by preventing equipment and lighting being open-circuited over short rail gaps, be of more advantage than the complete elimination of bus-line connection between cars?

Has there been any trouble arising from transfer of current through the roller axle bearings instead of through the brush-gear on the axle?

Because of the track layout of the terminal stations, without reversing spurs, it is impossible to route all arriving trains on to the left-hand platform road (as seen when approaching the station) and to use the other platform road for all departures. Therefore, the guard must change cabs either on entering the terminus or after leaving it (depending on which terminal platform the signalman has selected) in order to be on the correct side. This must be rather awkward operationally; what has been the experience?

Mr. W. E. Lewis: If an operator is willing to accept the high-speed motor, an axle-hung motor can be designed to run at these high speeds, using resilient gears; it will give equally quiet running and can be resiliently side located to the bogie. What, then, are the advantages of the right-angle drive?

[The author's reply to the above discussion will be found on page 527.]

DISCUSSION BEFORE A JOINT MEETING OF MEMBERS OF THE INSTITUTION AND OF THE ENGINEERING INSTITUTE OF CANADA, AT TORONTO, 12TH OCTOBER, 1954

Mr. A. G. Clark: What are the reasons for the prevalence of acceleration rates of 2–2½ m.p.h./sec? These rates are rather lower than those commonly found in North America surface-transport practice, e.g. street-cars and trolley coaches.

Mr. E. B. Augood: I should like more information on the dead-man pilot cut-off valve mentioned in Section 3.5. Does the driver have any indication of when he can legitimately release the master-controller handle? Has the attachment any real value?

Mr. C. V. Curran: Why was rheostatic braking not employed?

Mr. W. Sergeant: The paper refers only to cast-iron brake shoes; are the T.T.C. acquainted with the characteristics of non-metallic shoes?

I am rather surprised at the installation of the mercury retardation controllers, in view of the steepness and sharp changes of gradient of the line. At many locations the brakes could be applied under control of the retarder when some cars were on the gradient and some on the relatively flat section of the track. This could well lead to poor co-ordination of

ercury-tube operation with gradient, and I think that better rformance would result from having the tube in the centre of e train rather than in the leading car. Has this been tried?

Although it may not be economical to provide a rheostatic ake designed to make large speed reductions, in view of the gh proportion of down-grade running, would it be advanta- ous to adopt a form of coasting brake, such as is used on olley coaches?

Mr. S. Rosevear: Will the author indicate the wheel-tread thickness and flange dimensions?

Mr. P. Richardson: Why are the main starting resistors not used as a source of heat during the winter?

What is the practical or commonly acceptable upper limit of the installed horse-power per axle?

Will the author enlarge upon the design of the uncommon track gauge of 4 ft $10\frac{7}{8}$ in?

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. Frank W. Roberts (*in reply*): Members may be interested know that between the 30th March, 1954, and the 31st March, 55, the Toronto subway carried about 73 000 000 passengers d ran approximately 6 150 000 car miles in revenue service; r mileage averages 60 000 per year. Until January, 1955, 0 cars were available; the imminent arrival of two bodies will ing the total to 106, but the daily peak of 96 cars on the line s always been provided without difficulty.

Mr. Manser's remarks concerning low track voltage and high earbox temperatures were based upon unpublished reports; the rmer is due to heavy loading on an adjacent streetcar route d will be alleviated by the commissioning of a new substation, hile the latter hinges upon a single measurement. Neverthe- ss, it is agreed that hypoid-gearbox losses are greater than the nventional figures quoted in B.S. 173 for spur gears.

I will reply to the rest of the discussion by subject headings ther than by individual speakers.

Track.—The rolling stock cannot be converted to 4 ft $8\frac{1}{2}$ in uge. The origin of 4 ft $10\frac{7}{8}$ in is obscure and dates back to the d of the last century. The horse-drawn traffic of the day eferred the smooth angle-iron streetcar track to the rougher ad surface; 4 ft $10\frac{7}{8}$ in was the average vehicular wheel gauge d may have been adopted for the track as a public gesture. is believed that the only other example of 4 ft $10\frac{7}{8}$ in gauge is in . Louis, Missouri. The possibility of Toronto streetcars using ctions of future rapid-transit routes while parts are under nstruction cannot be dismissed. Thus a unified city gauge has erit. Consideration was given to a fourth-rail system, but it s thought not the best for this application. The amount of pper reinforcement to the return rail is small.

Freezing of exposed points in winter around Davisville is evented by 600-volt electric heaters; no trouble was experienced st year on either running or third rails anywhere on the subway stem.

Transmission.—The need to keep the motion of the rubber- ished universal joints within a solid angle of about 2° is rightly nphasized. It is true that hypoid gearing is heavier than ur gearing, but its quietness is an asset.

Acceleration.—In practice the choice of three rates of accelera- g current has not been used, and the feature may be simplified future to a 2-position link board. Since all axles are motored, e tractive effort is so far below the limit of adhesion that the fect of weight transfer was ignored. The published figure of 3 m.p.h./sec was the planned rate; although some increase in rting current was permitted, the present rate is about n.p.h./sec for an average car on level track. To facilitate xed multiple-unit working, the same accelerating rate is main- ned with the lighter (73 400 lb) aluminium cars constituting the t six of the present series, the current being reduced accordingly. cannot believe that Mr. Cock is serious in considering an celeration of 1 m.p.h./sec for a modern system with 12 stations a $4\frac{1}{2}$-mile route.

Braking.—Experience in Toronto has been that the potential vantages of composition brake shoes—not necessarily non- tallic—are great enough to warrant much experimenting to remove their few faults. Their life appears to be about four times that of cast-iron shoes at a price some three times greater.

Retardation controller.—The idea of revising the retardation-controller circuit is timely. There being little prior experience with subways in which braking points occur at severe changes of gradient, the London circuit was adopted. It is unlikely that the central retarder of the train will be put in control, but the possibility of connecting in parallel all the appropriate mercury tubes is in mind. It may be that the benefits accruing from having the most critical tube in control would assist in achieving the shortest practical running time, even at the expense of extra train wires. However, this is not a proven fact and needs much careful thought.

Traction motors.—The Commission's experience with more than 3 000 high-speed streetcar motors, some of which were made in Britain and all closely resembling its subway motors, does not support the fears that they may be unreliable or extravagant in maintenance. A simple device permanently attached to the subway car motor permits an external compressed-air line to be quickly connected and directs air down the armature core ducts, so that 6-monthly blowing out takes very little time. It is now generally accepted that tapped fields are undesirable where frequent breaks occur in the conductor rail; "transformer" effects have to be avoided, and an appreciable amount of additional cable is needed with a 4-motor circuit. On the matter of gear ratio, it is generally easier to obtain a high ratio with hypoid gearing than with spur; this simplifies the application of high-speed motors to railways with low schedule speeds.

With axle-hung motors the upper limit of installed horse-power is found on main-line railways, where 1 000 h.p. on a single axle is known; the power is associated with the higher speed of operation and is not even remotely approached by urban subways.

Power circuits.—It is felt that the omission of an inter-car bus line has more advantages than disadvantages when every axle of every car is motored. The use of a completely insulated earth return within the car positively prevents any 600-volt power passing through the axlebox bearings, except under earth-fault conditions; to date, no box has given any trouble at all.

Cab location.—The choice of platform at terminals is normally made automatically by the signalling system. After interpreting the signal aspect, the driver indicates to the guard by bell signal whether he should change sides to open the appropriate doors. This has caused no difficulties; the slight inconvenience to the guard is more than offset by the additional revenue-earning space in the car.

Heating.—A 50-volt fan motor was thought preferable to a small high-voltage machine; a pair of manually-reset bimetallic thermostats protects against overheating if a fan stops.

Sliding doors.—It is probable that a reduction will be made in the operating air pressure of the doors, but the small difference between its present setting and that of the traction control gear has caused no problems. The zoning feature has not yet been used but will be retained on the next 34 cars. I do not see how

the door safety interlocks and traction-control relay can introduce an unsafe condition, as Mr. Barton suggests; on occasion, mischievous persons have slightly opened a door when in motion, but the power is restored immediately the door is released. The equipmeet notches up very quickly under such conditions, and no ill effects are noticed.

Collector shoes.—Collector shoes are of malleable cast iron and are spring loaded to give a force of about 17 lb on the third rail. None has yet worn out; their life cannot be reliably forecast, but may be about two years at a rate of 60 000 miles per car per year.

Lighting.—The lighting load inside a 2-car unit is almost 4 kW, and to have supplied it at low voltage would have increased the motor-generator rating about 100%; this was thought uneconomic.

Wheels.—The data sought by Mr. Roseveare are these: flange depth, 1 in on radius; flange thickness, $1\frac{7}{8}$ in at 30 in diameter; rim thickness, $2\frac{3}{4}$ in when new.

DISCUSSION ON "ELECTRICITY IN THE WOOL-TEXTILE INDUSTRY"*

NORTH-WESTERN UTILIZATION GROUP AT MANCHESTER, 16TH MARCH, 1954

Mr. S. Birchall: Many mill owners who have recently bought new textile machinery with individual drives find that, with the engine load decreasing, they have surplus power available, and they have been considering installing alternators to load their engines to run at maximum efficiency. One example recently reviewed was on a 500 kW load; the weekly cost of generation was £145 (based on a coal consumption 2 lb/i.h.p. with coal at 74s. 0d. per ton), against a figure of £153 for purchased electricity.

With regard to conversion of a mill from engine driving to electric motors, I find that it is generally the boiler plant that has deteriorated most and that a mill of average size can be changed to electric driving for less than the cost of new boiler plant. A recent case under review showed that the cost of new boiler plant was £28 000, while that for complete electrification was £25 000.

With the smooth-acceleration motors referred to in Fig. 7 there is some diversity of opinion as to where the end breakage occurs. In my opinion it is not at the instant of switching on, but just before the motor attains full speed. It is therefore desirable that the torque/speed curve should not rise rapidly, but keep reasonably flat.

The authors say very little about the use of electronics in the textile industry, but there are several recent developments using photo-electric relays, one being the automatic stopping of speed frames, where a broken roving travels along a duct and passes through a beam of light shining on to a photocell, the interruption stopping the motor automatically.

Mr. G. M. Bracewell: In Section 4.2.4. the authors refer to the effect of machine temperature, lubrication and type of bearings on the load taken, and they give a curve in Fig. 11 showing the effect of cold starting. A similar case occurred during recent tests on cotton doubling frames, when it was noted that the maximum demand on the doubler at starting time Monday morning was 42% higher than the settled value at dinner time. After the machine had been stopped for one hour in the middle of a doff the same condition occurred, presumably due to solidification of grease on the doubling ring. The greasing operation is of some importance in keeping the driving power down, some managers preferring to grease after each doff while others grease every three doffs. For the larger ring sizes the latter is probably sufficient.

With regard to the type of bearings used; a test was conducted to determine the relative effect of plain- and roller-bearing spindles, the machines being otherwise identical. With both machines unloaded and at working temperature, the plain-bearing machine took 29% more power than that with roller bearings. When both machines were loaded with full bobbins under normal conditions, the power difference was 24%, again in favour of the roller bearings. Both machines had been installed a considerable time and were thoroughly run in. These effects are of considerable importance also in relation to ring-spinning frames of the large-package high-speed type, and in the absence of a strict maintenance and lubrication routine appear considerably to limit the economic counts range which might otherwise be spun on the machine.

A further test to determine the allocation of power supplied by the botton shaft of a $2\frac{1}{2}$ in-ring 12 in-lift frame with multi-spindle drive spinning 14's count at an experimental speed of 9 000 r.p.m. gave the following result: with the power supplied by the bottom shaft taken as 100%, it was found that 42% was taken by friction in the tape drive and spindles, 24% by the bobbin air-resistance and 34% in moving the traveller against the ring friction. The two latter factors are more or less inherent in the system, but I feel the authors may agree that the former factor deserves attention by machinery makers. It would appear that the load on a centrifugal spinning frame is mainly friction, possibly air friction, at the high speeds quoted. It would appear at first sight that the machine would have a restricted economic counts range, although this may not be so.

I agree with the authors that the smooth-acceleration motor can be used to advantage in obtaining a controlled run up to speed, but this is difficult to obtain when a wide counts range is required, particularly on large-package high-speed machines which require considerably more power for coarse counts than fine. The low-speed section of the resistance/torque curve is not much affected by counts changes, whereas the higher-speed section becomes steeper and an increased motor horse-power is required. This often results in the frame being overpowered for much of its duty, and snatch starting again tends to occur. A better solution may be to start the motor through a suitably tapped reactor, although whether this method would be economically acceptable would depend largely upon the size of the doffing team available to deal with starting-end breakages.

* FRANCIS, A. J., and CARR, T. H.: Paper No. 1563 U, October, 1953 (see 101 Part II, p. 291).

The authors refer in Section 4.3 to variable-speed driving for g-spinning frames, for which production increases up to 20% claimed. This increase should perhaps be qualified by the ative production efficiency of the mill in question before the plication of variable-speed driving, otherwise the technical vantages described are meaningless. In any case, it is possible control the balloon tensions without varying the speed by the plication of balloon control rings. By this method I have en able to raise the spindle speed of large-package machines 30% above the best contemporary standards, over a wide unts range and with a commercially acceptable end-breakage e. The primary difficulty with the system is restriction of the onomic counts range, owing to increased power costs, although s factor varies for different markets.

No direct comparison between variable-speed drive and lloon control has yet been made, but indications are that the ter system has technical advantages, simplicity and very low st not possessed by the former.

Dr. B. E. King: I should like to discuss three uses of electronic ntrols in the industry, the first being to woollen carding. The nsity of the web coming from the last doffer is measured photo-ctrically and the signal is used to control the speed of the doffer d slubbing motion, thus maintaining the web density more el; this equipment is now in use on a woollen card in a York-re mill. Another piece of equipment has been developed on principle of scanning a section of web with a photo-electric vice, the dense portions which form neps producing counts by erruption of the beam. The third device—also using the otocell—is a hopper-level control, used to maintain the level very open materials in fibre form at a constant head above a ir of delivery rollers. This is simply an electronic on-off itch.

Mr. J. G. Winterbottom: Conversion from steam to electric ive raises problems within the mind of the mill owner. He ay prefer the retention of his existing line-shafting simply cause he knows that this is the cheapest in capital cost. Have authors produced some analytical explanation, for use when proaching prospective power consumers, which illustrates in ms of financial savings the wisdom of the individual drive? they compute the frictional loads, as nearly as possible, ich are prevalent in the existing installation, taking into account bearing-pressure losses, heavy flat belts, unwieldly head-shaft drives, etc.? Mill owners might be more convinced of the advantages of electrification when it is dealt with in this way. Taking into account the diversity of load within the several departments of a given factory and a knowledge of actual running costs after conversion has been completed, I feel that the case for judicious individual machine electrification is very strong.

The raising of steam electrically to meet the heavy requirements of the dyeing and finishing sections would appear to be uneconomical, because the fluctuating peak demands do not coincide with the maximum electrical driving power loads. In view of the large quantities of steam needed, the running cost of electrical steam-raising, even with off-peak operation, would seem prohibitive.

A recent example of a cotton manufacturing and dyeing concern proves rather illuminating from this aspect. The maximum driving-power demand was 900 kW, and only 7 650 lb of process steam per hour was needed. The estimated capital cost for the all-electric scheme, including driving plant and electrode boilers, was £24 000 and the combined running cost was £35 143 per annum, working at 0·865d. per kilowatt-hour. Alternatively, by using a private pass-out turbo-alternator the capital cost was £42 000 and the running cost was £14 500 per annum. The first scheme would absorb some 9 750 MWh per annum, and the second scheme only 2 250 MWh. While the turbo-alternator method costs 75% more to install, its running cost would be nearly 60% less.

Is any method yet known of utilizing the existing steam shell boilers after electrification on public supply? By suitable insulation and blanking off the flues, immersion heaters might be introduced to raise steam at a pressure of 15–20 lb/in^2 during off-peak hours at a low cost for storage. In working hours there would be doubtless the normal unit charges. This may reduce capital expenditure and make electric heating more attractive, provided that the method could be made efficient.

Mr. A. Cotton also contributed to the discussion at Manchester.

[The authors' reply to the above discussion will be found on page 532.]

NORTH MIDLAND UTILIZATION GROUP, AT LEEDS, 19TH OCTOBER, 1954

Dr. N. H. Chamberlain: I would draw attention to the authors' tement in Section 4.2.6 to the effect that it is the extremely riable nature of a loom load which makes individual driving this case so much more satisfactory than lineshaft driving, for m inclined to maintain exactly the opposite opinion. The aracteristic feature of the power demand of a single loom is very high peak coinciding with the action of the picking echanism in projecting the shuttle across the loom. This peak of short duration, but the ratio of peak demand to mean mand throughout the cycle of the loom may, in woollen and rsted looms, lie between 2 and 3. The motor fitted, if indi-lual drive is considered, must have sufficient power to carry loom over the picking peak, or weak picking may result, or machine may stall on the pick. In consequence, a 1½–2 h.p. otor is used when the mean demand is of the order of ¾ h.p., as shown by the figures quoted in Table 7. As a result of this licy, the motor is running for most of the time less than half-ded and consequently at reduced efficiency and low power tor.

If, on the other hand, a sensibly designed group drive is used, which about 20 looms are driven from a 15 h.p. motor, these nditions do not arise. The picking peaks of the various looms are randomly distributed in time, and the motor has always a sufficient reserve of power to overcome individual peak demands, or even coincident peaks if they occur in not more than one-third of the looms simultaneously—an event whose probability is extremely small. Furthermore, financial considerations must not be underestimated. In the case quoted, 20 small motors, each with its own starting gear and individual wiring, must inevitably cost far more than one large motor, with one starter and wiring to match. True, there will be additional costs in shafting and belts, but even then the capital cost is decidedly in favour of the group drive; whilst in running and maintenance costs there can be no question that the group drive will be more economical. In my opinion the importance of the example illustrated in Fig. 9 is exaggerated. The shaft in question is of excessive length and is admitted to be slender, and even then the speed variations at the remote end fall within the limits ±1½%, a variation entirely without commercial significance in loom driving, since it is of short-period character and the mean speed is practically constant.

There appears to be a possible solution to this problem of inefficiency in individual loom drives, first propounded apparently by Demartini and Lukens (*General Electric Review*, 1949, **52,**

p. 11). These authors suggest the fitting of a flywheel to the armature shaft of motors used for individual loom drives. The picking energy is then supplied from the kinetic energy of the flywheel, and a motor whose horse-power is little in excess of the mean loom demand may be utilized. The motor must, of course, run continuously if this is done, and a clutch must be used to disconnect motor and loom as required. The flywheel is placed on the motor shaft rather than the loom mainshaft, because the much higher speed of the motor enables a correspondingly smaller flywheel to be used successfully.

Mr. E. J. W. Mitchell: Fig. 4 implies that there is a gradual change-over throughout the industry to the use of purchased electricity. Although this may apply in the manufacturing side and, to some extent, to combing also, I suggest that it is otherwise in the dyeing and finishing section. With its far greater usage of low-pressure steam for process work, this part of the industry provides an almost ideal application of the back-pressure steam turbo-generator, and in the dyeing and finishing group with which I am associated, covering some twenty-four works, we are not only maintaining the level of our generating capacity by this means but, where possible, increasing it.

No great difficulty is experienced in achieving a balance of steam and electrical demands, and the local Electricity Board has readily co-operated in arranging for parallel operation when changing over between the works plant and mains standby.

Section 4.1.4 refers to types of motor enclosures. We specify total enclosure for all drives, whether the operating conditions be wet or dry. Because of reported experiences elsewhere of "breathing" of totally-enclosed types, we have experimented with drainage plugs in the motor end shields for the purpose of removing any condensation, but we have found that little moisture ever found entrance—at any rate, not in sufficient quantity to do real harm or to warrant the added expense of the modification and subsequent additional inspections.

We have made one exception to total enclosure and that concerns the rotor-fed a.c. commutator motors employed on variable-speed drives, where, chiefly for reasons of physical dimensions, we employ a drip-proof enclosure. Excellent service has been given by these motors, and where the occasional breakdown has occurred, the cause can usually be attributed to misuse of the motor by the operating staff or to slack maintenance.

Commutation and brush-wear troubles on this type of motor have been negligible, despite frequent arduous working conditions of fluff, steam and chemical vapours. Only in one case among the hundred such drives in use did we experience persistent trouble from bad commutation and heavy commutator wear, eventually located to a trace of chlorine from a near-by bleaching range, and finally cured by an alteration in brush grade.

In Section 5.1, the authors rightly remark that good lighting is an essential to good work. Table 8 shows lighting wattage as only some 6% of total factory demand, whereas we find our lighting load approximates 15%. The rooms are lit to at least the statutory 6 ft-candles, but our higher demand may be due to a general preference for filament lighting over fluorescent.

In Section 5, little reference is made to electronic control systems, which is surprising, because their use in the textile industry is rapidly growing, despite the doubts of many works engineers as to their effectiveness and reliability.

We have found that robustness is often lacking in some of the equipment put forward for industrial use. For example, wax insulant has softened and flowed under high, but not excessive, ambient temperatures; the power ratings of resistors have been inadequate; fine-wire soldered connections have suffered from fatigue failures as a result of vibrations transmitted from nearby machinery, and the air-gaps of micro-relays have needed frequent adjustment. With the accumulated knowledge of the hazards of industry which is available to electronics manufacturers, such troubles should not nowadays occur.

Nevertheless, despite such weaknesses, electronic controls have proved extremely valuable: for example, in a cropping machine for the detection of the cloth seam and raising the cutters to allow the seam to pass between them without stopping the machine, instead of "plugging," and for guiding slack fabric on to the stenter, where the lack of tension in the selvedge precludes the satisfactory use of the conventional finger-type detector.

On the other hand, where we have to match the speeds of two or more separately driven sections of a process machine, we have hitherto found that an a.c. variable-speed shunt-characteristic commutator motor of the Schrage type has proved perfectly satisfactory, with up to six drives in tandem, using only simple compensator, or jockey-roller, control of brush position for adjustment of speed.

Section 6 could, I think, have usefully included some information on substation and works distribution layout.

We ourselves adopt a system of works mains distribution at 415 volts, 3-phase 4-wire, using $0 \cdot 3\,\text{in}^2$ p.i.l.c.s.w.a. cable and serving radial feeders from the substation, each terminating at a 300 amp unit-type sub-main distribution switchboard equipped with h.r.c. fuse-switchgear for the outgoing cables. The fourth core is extended as far as the sub-main fuseboards and has proved of great convenience.

Main substations are usually equipped with oil circuit-breakers, but in view of the infrequency of operation under fault or overload conditions, one wonders whether things could not be simplified, without sacrificing essential reliability, by utilizing fuse-switchgear here also, either of the striker-pin release type or of ordinary h.r.c. type, incorporating, say, earth-leakage warning.

Mr. S. T. Clark: I would like to make some observations on Dr. Chamberlain's remarks.

Good power factor and efficient running of electric motors is an important and desirable objective. I do not, however, agree that it is so important in weaving that it defeats any arguments used by the authors. The loom tuner is convinced that there are fewer mechanical breakages, and that weaving conditions are better, on a loom driven by its own motor. This, coupled with constant speed, results in increased production. The woollen manufacturer, therefore, converts his loom to individual drive. After all, it is "picks that count."

Further, Dr. Chamberlain judges the efficiency of the motor by the number of picks per kilowatt-hour. In a number of tests taken ten years ago over many millions of picks, using pick counters and watt-hour meters, individual drives were found to be more economical than group driving. Single automatic looms driven by $1 \cdot 5$ h.p. motors produced 3% more picks per kilowatt-hour than a group of 14 similar looms belt driven through shafting with oil-ring bearings and a 20 h.p. motor. This was when all the looms were in operation, and weaving conditions for both types of drive were reasonably constant. Records show that the group motor, shaft and belts, without any looms running, gives a load of 4 kW, and that, if less than the full number of looms are working, the percentage difference between the two types of drive is increased. This is important in days of absenteeism and shortages of warp and weft.

Mr. R. Gibson: The authors have stated that, owing to space limitations, the Section on "Control of Machines" has had to be severely curtailed. I should, nevertheless, like to point out the increasing tendency towards the use of light-current electrical apparatus for actual control of certain processes.

In the past, settings of machines have generally been fixed during a run, so that what came out was very much a function of what went in, the machine itself having no information about

output product, and merely performing a preset operation the variable input material.

f the output of the machine can be continuously measured, l if by varying some aspect of the machine the ratio of output input can be varied, it is often possible to use a closed-loop ntrol system to maintain the output at a constant value regard- s of input variations or machine variations. For example, ctrical equipment now available for woollen carding machines asures photo-electrically the thickness of the carded web, and voltage representing the difference between the measured ckness and some desired thickness is amplified and fed to a all servo-motor which alters the speed of the doffer cylinder such a way that the error in web thickness is reduced, theo- ically to zero.

n a similar way (for the worsted trade) such important antities as sliver thickness and drafting force could be con- lled, and it often happens that the flexibility of electrical thods of measuring and controlling these quantities is usefully plied to experimental work, or to machines dealing with small nples.

May I also mention the various pieces of electrical apparatus w being used in the testing laboratory for quality control. ese measure irregularity in yarn diameter or in weight per t length, moisture content, fibre length, cloth strength and on.

Mr. A. J. Coveney: In view of the point which has been raised previous speakers concerning the choice of oil circuit-breakers h.r.c. fuses, I am prompted to add my comments. In general, course, both fulfil the demands of control in their own particu- way, and the important question which must be decided arding distribution is that there must be correct grading of all cuits to ensure rapid interruption of supply under fault con- ions, and at the same time maintenance of supply to healthy cuits.

This discrimination can be readily obtained with the use of rectly graded h.r.c. fuses, more easily and more cheaply than using oil circuit-breakers with protective relays, and to this re is the added advantage of the high-speed cut-off effect of smaller cartridge fuses; they are most useful in industrial l mill types of distribution, where usually the source of pply is adjacent to the load. With a voltage not exceeding volts, the fault currents can be of appreciable magnitude.

recollect one instance some years ago, where a Bradford mill erated its own supply by means of two 1 500 kW 400-volt hase alternators. The failure in a distribution box in a shed oining the power house resulted in many thousands of amperes ving before the back-up overload protection on the main oil- cuit-breaker feeder tripped, with obviously disastrous results he box and danger to personnel.

The question, therefore, whether an oil circuit-breaker or a tridge fuse should be used is a matter for technical study to criminate correctly for high-speed fault clearance, and on the aller circuits there is no doubt that the h.r.c. fuse does vide this essential feature.

Mr. M. E. Broadbent: Fig. 1 does not seem to give quite the picture since it indicates that all worsteds are dyed in the ce, but that is not so in the case of fine worsteds. None of the t cloth in this room was dyed after it was woven. It was d at the yarn stage—"top dyeing," I believe it is called— ween wool combing and spinning, and, if I may be forgiven comment, Bradford may be the centre of the worsted industry, it certainly is not the centre of the fine-worsted industry.

With reference to Section 3.3, it is appreciated that there is iation in steam demand for process work, but in spite of this there are numerous efficient and successful installations of combined power generation and process heating. Such factories often require carding and mule spinning departments to run night shifts when no process steam is required. The demand on the public mains is therefore confined to unrestricted hours, and they can take advantage of the off-peak tariffs, giving a very low overall running cost per annum.

While Figs. 4 and 5 show that we have much to be proud of, I feel that we must not jump to the conclusion that all the development in the wool textile industry is due to the efficiency of the electrical industry. Much progress has no doubt been due to the intrinsic worth of our electrical equipment, but much has also been due to the fact that boilers have been condemned, and engines have worn out after 100 years of use, and that electrification from the supply mains has been the least expensive alternative. I have no doubt the West Riding manufacturers appreciate the tidying-up they get with individual drives and good lighting, but the promised increased production must be a fact, and the suitability for short-time or overtime working is always in the background. The influence of taxation is a major factor of encouragement in the electrical equipment of factories.

I hardly agree that it is necessary for the entire set of carding machines to be started and stopped simultaneously; I would rather say that in certain classes of trade it is advisable. In my experience, it has generally been found quite possible to run carding and scribbling drives quite independently.

I agree that the question of lubrication of spinning frames is important. We have sometimes found that by changing to the correct lubricating oil a reduction in load of 1 h.p. can be effected on a spinning frame taking $7\frac{1}{2}$ h.p. In assessing the horse-power required it is most important to remember those cold mornings when for the first 20 minutes or so the average spinning or twisting frame can take, say, 20% more driving than normally. The motors must be large enough to cope with this, and it is particularly important to watch it where totally-enclosed motors are used in which no continuous overload capacity is specified.

I presume that the limited reference to lighting is due to limitation of space and the fact that the subject is well covered in illuminating engineering papers, but I am sorry a little more space could not have been devoted to Section 6, on distribution. The use of overhead busbar systems for power distribution in wool-textile factories has great merit, especially in most spinning and twisting departments. It provides a clean and safe layout, with a considerable degree of flexibility. There is usually less voltage drop, the protection, whilst adequate, being reduced to the minimum. With the tree system of distribution there is sometimes a tendency to over-protection. In multi-storeyed factories, one run of overhead busbar can be arranged to feed two floors, thus reducing initial cost without impairing the system.

Regarding the use of oil circuit-breakers or air-break switches with h.r.c. fuses on main distribution circuits, I wish the authors could have enlarged somewhat on the relative merits of each.

It is a good thing that the new electricity tariffs do not require separate circuits for lighting and power. In some districts the distinction used to mean an added cost without very apparent advantages. Although perhaps not very relevant to the paper, I should have appreciated some reference to the improvement of power factor, with comment on the advantages and disadvantages of the various methods of its improvement.

In attaining its objective of increased output per operative, the industry will no doubt look to electricity for assistance, and I am sure that assistance will be forthcoming in power driving, electronic controls and other services.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. A. J. Francis and **T. H. Carr** (*in reply*): The question of conversion from steam to electric driving and the relative running costs is raised by Mr. Birchall and Mr. Winterbottom. It is our experience that, with present-day costs, it is usual to show a saving with electric driving. Prior to 1939 it was often necessary to convince mill owners, by taking careful tests, that a saving in running costs would be achieved by adopting electric driving. To-day this is very rarely called for, and the advantages of individual driving are generally recognized, although it is difficult to assess the cash value of many of them. We regret that space limitations precluded us from dealing with the application of electronics to the textile industry, but we are grateful for the information on this subject given by Dr. King.

Mr. Bracewell mentions the difficulties of cold starting of machines such as spinning or doubling frames. We agree that it is very important that there should be efficient lubrication of these machines, and that the type and grade of lubricant used has a pronounced effect on their starting and running. These matters should be taken into consideration when making tests of power taken by machines. We are interested in his analysis of the load on a ring-spinning frame, and agree that the power taken in overcoming friction in the machine appears excessive and merits the attention of the machinery makers. We would also point out that a lot of unnecessary load might be added by the faulty adjustment of gears and excessive pressure on drafting rollers. We have not met with the starting difficulties on spinning frames that he has encountered, possibly because the counts range demanded from spinning frames in the wool-textile industry does not appear to be as great as he has experienced, presumably, in the cotton industry. We would suggest that a method of starting cheaper and simpler than a tapped reactor would be to revert to a continuously running motor with a flat-belt drive and fast-and-loose pulleys.

Mr. Winterbottom also raises the problem of providing heat for process requirements. We feel that where a combined power- and heat-generation scheme can be shown to be advantageous from a thermal and economic point of view, it should be adopted in the national interest. The difficulty with this is that the heating demand is very variable and its peaks do not usually coincide with the power-demand peaks. The production of large bulk quantities of heat by electricity is not economic on present-day costs, and the best solution would appear to be by raising steam with solid fuel in the existing boilers at a reduced pressure. When conditions are such that it is economic to use electricity for process heating, it is our opinion that the problem will have to be met along different lines, eliminating all the inefficiencies of the existing methods, e.g. by thermostatically controlled heaters on the machines where the heat is being used.

We are very interested to have Dr. Chamberlain's opinions on loom driving, but we still hold to the belief that the individual drive is the best method. For reasons stated in the paper, we contend that the running efficiency of the motor is of minor importance compared with the production efficiency of the loom. It is undoubtedly borne out by experience that higher and better output is obtained by driving looms individually, and we grateful to Mr. Clark for giving us his support in this matt which is backed up by his long practical experience in the tex industry.

Fig. 9 is only one example of what happens in a shaft driv a number of looms, and there is no doubt that there are ma worse examples in practice. There have been cases when it h been difficult to operate looms satisfactorily in certain parts lineshaft-driven weaving sheds owing to this cause. Th extremely variable nature of the loom load makes each loo interfere with its neighbours when driven from a common sha and to reduce this effect means stouter and more expensive lin shafting and equipment. Taking into account all the oth advantages of individual driving, most people to-day are co vinced that this is the best method of driving looms. We a aware of the suggestion for driving looms by a motor fitted wi a flywheel, and should be pleased to have more information this subject. This method might still further improve t efficiency of individual loom driving.

We are grateful to Mr. Mitchell for giving us his experience electrical driving in the dyeing and finishing sections. W reference to factory lighting, Table 8 is the analysis of load in woollen mill. We have no figures for lighting loads in the dyei and finishing sections, but we think that the proportion lighting load to total load will be higher in this section, owing the more scattered layout of machinery. We are very interest in Mr. Mitchell's remarks about electronic methods of contr and also those of Mr. Gibson. This subject has merely be noticed in the paper, and no attempt has been made to de with it, owing to limitations of space, but we do feel that it very important and is going to play a prominent part in futu development, and we would suggest that there is scope for paper devoted entirely to this subject.

Mr. Coveney raises the question of adequate protection f circuits in the internal distribution system of a mill, and discuss the advantages of h.r.c. fuses. The only disadvantage we kno with ordinary air-break switch-fusegear is that it is possible f one fuse to blow and leave motors "single-phasing" with possibility of consequent damage, although we do not know any instances where this has happened.

We agree with Mr. Broadbent that some worsted yarn produced from wool which has been dyed in the top, whi necessitates another process known as "recombing." This w not shown in Fig. 1, because, whilst this is meant to give comprehensive idea of the industry, it cannot show all the ma variations without being very complicated. With regard combined power and heating schemes, where these can be show to be advantageous from a thermal and economic point of vie they should be adopted. We do not agree that electrical drivin is being installed in mills because it is the least expensive altern tive. Electrical driving has many important advantages, an these are now widely recognized, although, in many cases, w agree that an engine breakdown or a failure of boilers to pa insurance examinations often forces the issue.

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Paper No. 1798 U
March 1955

THE STANDARDIZATION OF RETAIL ELECTRICITY TARIFFS

By A. O. JOHNSON, B.Sc.Tech., and N. F. MARSH, M.A., Members.

'he paper was first received 30th August, and in revised form 28th November, 1954. It was published in March, 1955, and was read before the NORTH-WESTERN UTILIZATION GROUP 15th March, a JOINT MEETING of the SUPPLY and UTILIZATION SECTIONS 17th March, and the NORTH-EASTERN CENTRE 28th March, 1955.)

SUMMARY

The aim of the authors is to review the general position with regard the standardization of retail electricity tariffs in those parts of Great ritain served by the fourteen Area Boards.

Broadly, the paper covers:

(a) The situation at vesting date (1st April, 1948).
(b) How tariff standardization has been tackled.
(c) The progress so far made in the introduction of standard tariffs.
(d) Problems encountered in introducing standard tariffs.

Tariffs for domestic, industrial, commercial and farm consumers and r combined premises are considered. Notes are included on tariffs the North of Scotland and Northern Ireland, and brief references e made to salient points of comparable tariffs in some other European untries.

(1) INTRODUCTION

The Electricity Act, 1947, placed a duty on Area Boards to mplify and standardize tariffs, and it laid down that until such ne as standardization was effected the existing tariffs should main in operation.

The simplification and standardization of tariffs was not easy solution because there were at vesting date 541 separate ectricity undertakings, each of which had its own tariff strucres probably embracing in the aggregate upwards of 5 000 fferent tariffs.

Standardization of tariffs was not a new problem; it had been nsidered by many committees long before vesting date, but til the electricity supply industry was nationalized it was fficult to take the co-ordinated action necessary to effect major riff changes.

(1.1) Tariff Committees set up prior to Vesting Date

During the 25 years preceding vesting date a number of comttees were set up at different times to examine and report on the tariff structures in this country. The more important these committees were as follows:

(a) 1925.—Tariffs Committee appointed by the Electricity Commissioners.
(b) 1927.—Rural Areas Prices Sub-Committee of the Conference on Electricity Supply in Rural Areas—appointed by the Electricity Commissioners.
(c) 1929.—Uniformity of Electricity Charges and Tariffs Commmittee—appointed by the Electricity Commissioners.
(d) 1941.—A Sub-Committee of The Institution of Electrical Engineers Post-War Planning Committee.
(e) 1943.—Incorporated Association of Electric Power Companies' Sub-Committee on Standardization of Tariffs, Voltages and Assessments.
(f) 1946.—Uniformity of Tariffs Committee—appointed by the Electricity Commissioners.

It is not proposed in the paper to examine the recommendations these committees and sub-committees in view of the fact that, lowing the nationalization of the electricity supply industry, a ther body known as the Retail Tariffs Committee was formed re-examine the whole tariff position in the light of the cirmstances existing at that time.

(1.2) Retail Tariffs Committee

The Retail Tariffs Committee was set up in 1948 by the Central Electricity Authority and the 14 Area Boards and consisted of four representatives of the Authority and the Chairman or Deputy Chairman of each Area Board.

The main recommendations of the Retail Tariffs Committee are set out briefly in succeeding Sections, but it must be borne in mind that some of these recommendations have been made only recently and consequently there has not yet been time to put them into effect.

(2) RELATIVE IMPORTANCE OF CONSUMER GROUPS

Subsequent Sections of the paper deal separately with each main class of consumer, but it may be useful to have in mind an overall picture of electricity sales in relation to the numbers of consumers in the main groups.

Fig. 1 shows in respect of the year ended 31st December, 1953, the number of consumers in each group expressed as a percentage of the total number of consumers, and also the energy sold to each of the same groups expressed as a percentage of the total.

It will be seen that whilst in the cases of the commercial, combined-premises and farm groups, the percentage relationships of number of consumers and energy sold are approximately equal, the domestic group, representing 87·8% of the total number of consumers, purchased only 31·6% of the total energy sold, whereas the industrial group, representing only 1·3% of the total consumers, purchased 52·6%.

(3) DOMESTIC TARIFFS

Domestic tariffs have to cater for a wide range of types and times of utilization, and the tariff structure must therefore take account of the responsibility of low load-factor users for capacity costs and at the same time afford progressive advantage for consumers with higher load factors.

As a group, domestic consumers spread their use of the supply from early morning to late at night and help to fill up some of the valleys in the daily load curve.

(3.1) Domestic Tariffs at Vesting Date

Fig. 2, which deals with the position at vesting date, shows the proportion of the total number of domestic consumers being supplied on the main types of domestic tariffs.

It will be seen that the highest percentage of consumers (57·1%) were supplied on two-part tariffs, that 30·4% of consumers were supplied on flat-rate tariffs, and only 11·4% on block tariffs.

With regard to methods of assessment of fixed charges in two-part tariffs and primary blocks in variable-block tariffs, the rateable-value basis applied to 29·1% of the consumers, the floor-area basis to 21·0% and the rooms basis to 12·4%.

The rateable-value basis was mainly in use by the former municipal supply undertakings, for whom it was obviously convenient, and this basis was retained by such undertakings even when their area of supply was extended beyond the boundaries of the area for which they were the rating authority.

Mr. Johnson is with The North Western Electricity Board.
Mr. Marsh is with The North Eastern Electricity Board.

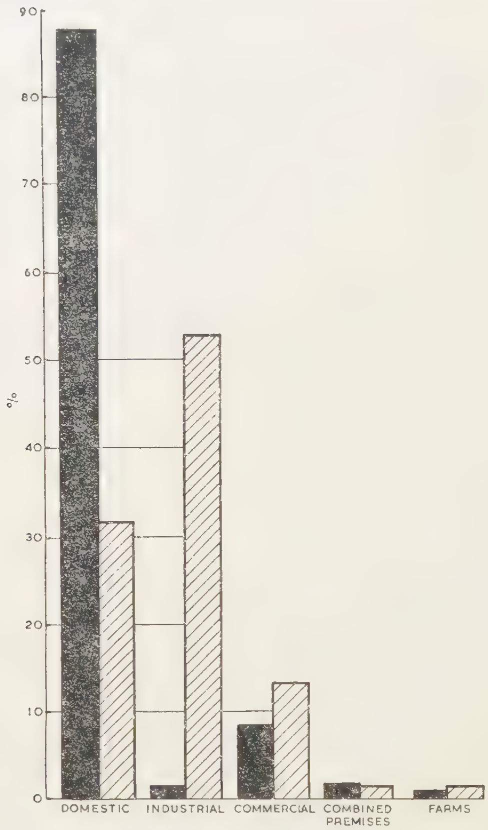


Fig. 1.—Number of consumers and kilowatt-hours sold in the five main consumer groups for the year ended 31st December, 1953, shown as percentages of the total number of consumers and total number of kilowatt-hours sold, exclusive of public lighting and traction.

Percentage total consumers.

Percentage total kilowatt-hours.

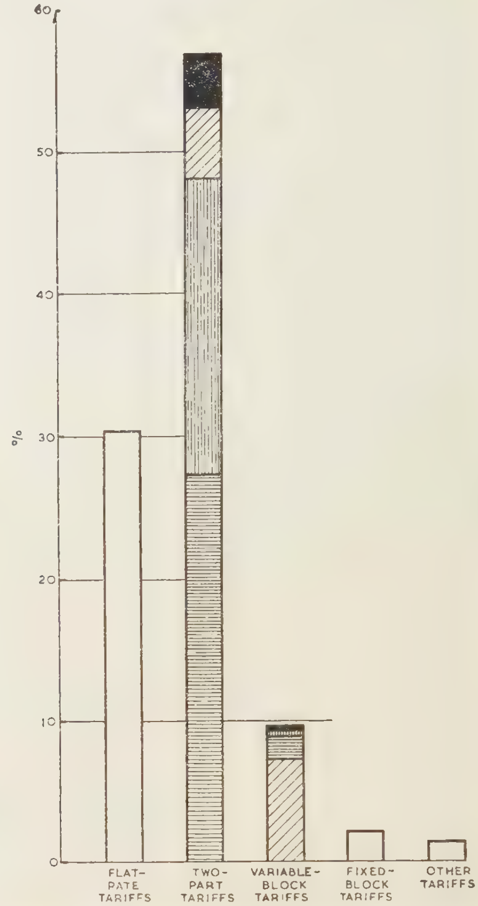


Fig. 2.—Domestic consumers supplied on the main types of tariff 1st April, 1948, shown as percentages of the total number domestic consumers.

Rooms. Rateable value.

Floor area. Other bases.

Many company undertakings, on the other hand, provided supplies in areas administered by a number of different rating authorities, and because of differences in bases of rateable value assessments within their areas of supply, had adopted floor area or number of rooms as the bases for their domestic tariffs.

(3.2) Domestic Tariffs Recommended

The recommendations of the Retail Tariffs Committee as to the structure to be adopted by Area Boards for domestic tariffs are as follows:

Each Area Board should have discretion to adopt:

(*a*) A two-part tariff and an alternative flat rate.
(*b*) A variable-block tariff with two or three blocks.
or (*c*) Both a two-part and a variable-block tariff, side by side, on a broad equivalence.

The assessment of the fixed charge of two-part tariffs and the primary block of block tariffs should be based on either:

(i) The number of rooms in the premises.
or (ii) The floor area, with a recommendation in favour of the number of rooms.

The two main points worthy of note in these recommendations are the choice of tariff structures which permit of single metering and the omission of rateable value as a method of assessment.

The Committee's definitions of rooms and floor area are:

Rooms.

"Rooms" shall include all rooms, whether used or not, a whether wired for electricity or not; rooms with structural divisic such as fixed or folding partitions to count as two or more as the ca may be; the following rooms to be excluded: entrance halls vestibules, larders, sculleries (if additional to kitchen or kitchenett cloakrooms, closets, lavatories or w.c.'s, bathrooms, attics witho access by permanent staircase, store-rooms, boxrooms or cellars such rooms or cellars are without external window, central heati chambers, washhouses, coal stores or coal cellars, garag greenhouses.

Floor Area.

Where the floor-area basis of assessment is adopted the expressi "private dwelling house" shall include any building (attached detached) within the curtilage, but shall exclude any portion of su premises used for trade purposes or for the lighting of which t consumer is not responsible, or any garage, or any detached buildi used solely for storage.

For the purpose of ascertaining the fixed charge the Board w obtain the size of the house in terms of square feet by taking extern measurements of the private dwelling house at the ground flo level and multiplying the area thus obtained by the number storeys in the house, due allowance being made for part floors.

(3.3) Procedure for Fixing Standard Domestic Tariffs

Before the formulation of a standard domestic tariff could commenced in any area the Area Board first had to consid

ich of the recommendations of the Retail Tariffs Committee wished to adopt and then to discuss the proposed basis with e Area Electricity Consultative Council.

Having decided upon the tariff structure to be adopted a ajor problem was to secure the necessary information on which e tariff could be calculated.

Although neither the rooms nor the floor-area basis of assess-ent was new, in no Board's area was it found that all the former dertakings had used the assessment bases and definitions now be adopted as standard. It was therefore necessary to obtain e basic data as to number of rooms or floor area in respect of the domestic premises concerned, and this was done in rious ways.

It is not practicable to describe here the methods adopted by ch Area Board, but the following is the method which was opted by one Board and which can be dealt with in some detail.

The Board had decided to adopt a variable-block tariff of the o-block type based on the number of rooms, and in order to certain the number of assessable rooms consumers were quested to provide the requisite information in respect of their vn premises by completing and returning a suitably designed epaid postcard.

A sample of the completed cards returned by consumers was ected by statistical methods to ensure that it was representative all the domestic consumers. The final sample consisted of me 210 000 consumers, or between one-fifth and one-sixth of e total number of domestic consumers.

Most Boards decided to fix the price per kilowatt-hour of the imary block at about the average of the then existing flat-rate hting tariffs and the follow-on rate for all energy used in cess of the primary block at the prevailing running charge in e domestic all-in tariffs.

It is obvious that in a large area with a multitude of tariffs any rm of standardization must result in increased charges to some nsumers, and lower charges to others, whilst some will perience little or no variation. In the initial stages at least the ost acceptable tariff would therefore be the one which not only cured the desired total revenue from the consumers as a whole, t at the same time involved the minimum alteration in total venue from the consumers in each room group.

In the case of the Board previously mentioned, several tariffs re formulated which appeared to hold promise of fulfilling these quirements, and Table 1 shows the overall effect of applying ree slightly different tariffs, while Fig. 3 shows the estimated

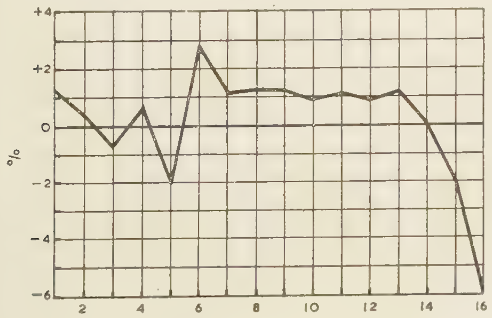


Fig. 3.—Standard domestic tariff: percentage by which estimated revenue from standard tariff varies from former revenue.

rcentage revenue variation of each room group produced by tariff which was finally adopted.

Fig. 4 relates to two former undertakings and shows the annual netary disturbance to the consumers in those areas.

Table 1

REVENUE DISTURBANCE BY ROOM GROUPS OF THREE TENTATIVE DOMESTIC TARIFFS

Data	Number of rooms: 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16 and over	Total
Number of consumers	420	7 625	26 427	346 373	310 947	340 951	67 028	28 868	12 754	5 886	3 096	1 666	858	532	294	432	1 154 157
Percentage of total consumers	0·04	0·66	2·29	30·01	26·94	29·54	5·81	2·50	1·11	0·51	0·27	0·12	0·08	0·05	0·03	0·04	100
Consumption (kWh × 10^6)	0·256	3·676	18·644	253·750	307·359	488·733	137·306	80·963	42·044	24·030	14·372	8·873	5·120	3·016	1·838	3·636	1 393·616
Percentage of total consumption	0·02	0·26	1·34	18·21	22·05	35·07	9·85	5·81	3·02	1·72	1·03	0·64	0·37	0·22	0·13	0·26	100
kWh per consumer	609	482	705	733	988	1 433	2 048	2 805	3 297	4 083	4 642	5 326	5 968	5 670	6 253	8 417	1 207
Present position:																	
Revenue, £	1 862	31 191	131 547	1 774 035	1 939 185	2 800 104	760 611	427 726	221 456	123 782	73 810	45 232	25 934	16 070	9 994	19 427	8 401 966
Percentage of total revenue	0·02	0·37	1·56	21·07	23·06	33·35	9·08	5·10	2·64	1·48	0·88	0·54	0·31	0·19	0·12	0·23	100
Revenue per consumer, £	4·43	4·09	5·0	5·10	6·24	8·21	11·35	14·82	17·36	21·03	23·84	27·15	30·23	30·21	33·99	44·97	7·28
Tariff 1:																	
First block kWh/quarter	34	34	34	34	42	50	58	66	74	82	90	98	106	114	122	130	
Estimated revenue, £	1 843	30 552	127 875	1 746 122	2 015 406	2 934 456	762 214	423 052	216 570	119 922	71 185	43 371	24 798	15 069	9 153	17 111	8 558 699
Difference from existing tariffs, £	−19	−639	−3 672	−27 913	+76 221	+134 352	+1 603	−4 674	−4 886	−3 860	−2 625	−1 861	−1 136	−1 001	−841	−2 316	+156 733
Percentage variation from existing revenue, ± %	−1·0	−2·1	−2·9	−1·6	+3·8	+4·6	+0·2	−1·1	−2·2	−3·1	−3·6	−4·1	−4·4	−6·2	−8·4	−11·9	+1·8
Tariff 2:																	
First block kWh/quarter	32	32	32	32	41	50	59	68	77	86	95	104	113	122	131	140	
Estimated revenue, £	1 797	29 695	124 804	1 701 136	2 002 700	2 938 622	767 071	426 891	219 011	121 441	72 196	44 025	25 187	15 347	9 332	17 407	8 516 662
Difference from existing tariffs, £	−65	−1 496	−6 743	−72 899	+63 515	+138 518	+6 460	−835	−2 445	−2 341	−1 614	−1 207	−747	−723	662	−2 020	+114 696
Percentage variation from existing revenue, ± %	−3·5	−4·8	−5·4	−4·3	+3·2	+4·7	+0·8	−0·2	−1·1	−1·9	−2·2	−2·7	−2·9	−4·5	6·6	−10·4	+1·3
Tariff 3:																	
First block kWh/quarter	36	36	36	36	36	48	60	72	84	96	108	120	132	144	156	168	
Estimated revenue, £	1 888	31 392	130 929	1 790 697	1 901 778	2 893 201	770 684	433 915	224 579	125 089	74 765	45 730	26 243	16 087	9 816	18 233	8 495 026
Difference from existing tariffs, £	+26	+201	−618	+16 662	−37 407	+93 097	+10 073	+6 189	+3 123	+1 307	+955	+498	+309	+17	−178	−1 194	+93 060
Percentage variation from existing revenue, ± %	+1·4	+0·6	−0·5	+0·9	−2·0	+3·2	+1·3	+1·5	+1·4	+1·1	+1·3	+1·1	+1·2	+0·1	−1·8	−6·2	+1·1

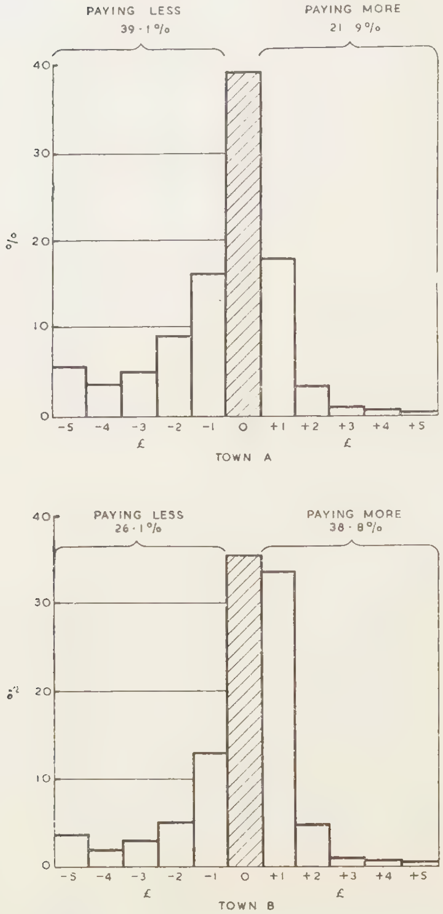


Fig. 4.—Standard domestic tariff: annual monetary disturbance to consumers in the areas of two former undertakings.

(3.4) Domestic Tariffs at the End of 1953

Of the thirteen Area Boards which have so far standardized their domestic tariffs, the position is as follows:

Ten Boards have adopted variable-block tariffs based on the number of rooms, eight of which tariffs are of the two-block type and two of the three-block type.

Two Boards have adopted two-part tariffs based on floor area. One of these Boards has also provided as an alternative a fixed-block tariff of the three-block type.

One Board has provided both a two-part tariff and a variable-block tariff, each based on the number of rooms.

The majority of these Boards have also provided a prepayment meter tariff.

The marked change which has taken place during the period since vesting date is indicated in Fig. 5, which shows the percentage of domestic consumers supplied on the main types of domestic tariffs at 31st December, 1953.

It will be seen that 88·4% of all domestic consumers are now supplied under standard tariffs; the majority (67·5%) are on variable-block tariffs all based on rooms assessment, 19·3% are on two-part tariffs (17·3% based on floor area and 2% on rooms), 1·6% of the consumers are on other types of standard tariffs and only 11·6% remain to be changed over to standard tariffs.

(3.5) Experience in introducing Standard Domestic Tariffs

(3.5.1) Rooms Assessment.

Of the alternative bases of assessment recommended by the Retail Tariffs Committee the rooms basis is the simplest to introduce. Any difficulties which have arisen have been due to different interpretations of the definition of rooms to be assessed.

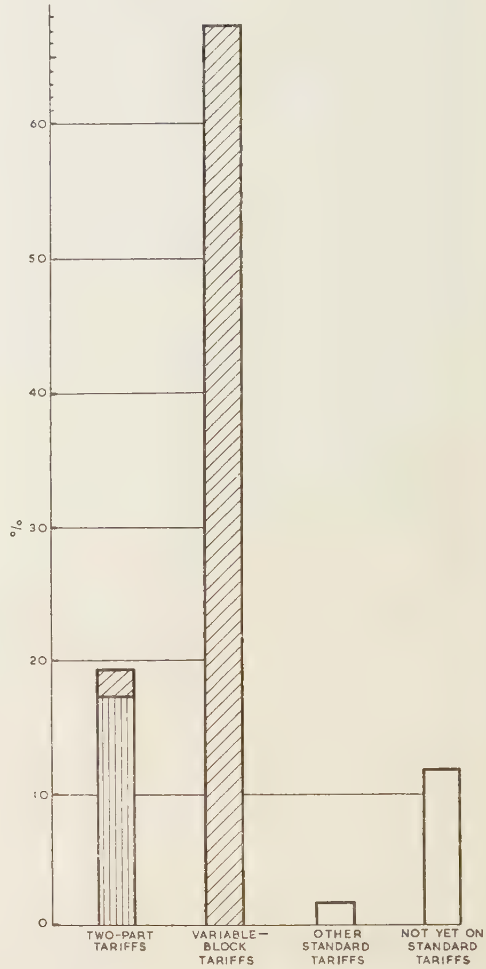
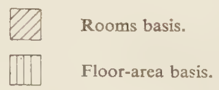


Fig. 5.—Domestic consumers supplied on the main types of tariff 31st December, 1953, shown as percentages of the total numbe domestic consumers.



As the definition was recommended for application through the fourteen Boards' areas, it naturally represents something o compromise, and it follows that words used to describe a p ticular room in one part of the country do not necessarily ha quite the same meaning in other parts. This applies particula to such rooms as kitchens, kitchenettes and sculleries. The m difficulties encountered with the assessment of rooms a methods of dealing with them are as follows:

Sculleries and Kitchenettes.—It is considered that there should included in the rooms assessment of each house the room in wh the food is normally prepared and/or cooked. In many of smaller-type houses, however, the food is prepared and/or cool in a room which is normally described by the consumer as a scull and the room which is called by the consumer a kitchen is virtu the living-room of the house. In the authors' experience it necessary in these cases to include the so-called scullery in the roo assessment, since the purpose for which it is used is no differ from that of the kitchen or kitchenette in many other houses flats. It is probable that less difficulties would have been experien if all sculleries had been included as assessable rooms.

Attics and Cellars.—The inclusion in the rooms assessment attics approached by a permanent staircase and cellars with exte windows may in some cases cause hardship where these rooms not used. To exclude these rooms completely from the assessm

would, however, be unfair since many attic rooms are used as bedrooms and many cellars or basement rooms are used as kitchens or even living-rooms. It is considered that the only practicable way of dealing with this matter is to allow the Boards' assessors some discretion to omit attics and cellars in cases where they are clearly unlikely to be used.

Large Houses partially inhabited.—Here again it is considered that some discretion must be allowed to local assessors to omit from the assessment unused rooms in large houses. It has been suggested that this difficulty might be overcome by fixing an upper limit to the number of assessable rooms, but this does not always meet the case since it is not necessarily the large mansion-type house which is adversely affected by the inclusion of all assessable rooms.

Inclusion of rooms whether or not wired.—The authors are satisfied that all rooms (other than those specifically excluded by the definition) should be included as assessable rooms irrespective of whether or not they are wired for electricity. To do otherwise would encourage the partial wiring of premises and necessitate frequent checking of assessments. Moreover, if the number of assessable rooms was decreased by any concessionary exclusion of unwired rooms the resulting loss of revenue would have to be made good by increasing the number of primary kilowatt-hours per wired room.

5.2) Floor-Area Assessment.

Floor area as a basis of assessment for domestic premises ffers from the main disadvantage that it necessitates expert easurement of most of the premises before a standard tariff can introduced and measurement of a very large number of emises before the tariff can even be formulated.

Floor-area assessment tends to operate to the disadvantage of nsumers living in older premises which have a greater propor-on of floor area taken up by passage ways, box rooms, store oms, etc., as compared with the floor area taken up by bitable rooms. On the other hand, it avoids the difficulties hich have been experienced with the rooms basis in the assess-ent of kitchens and sculleries.

.6) Domestic Tariffs in the North of Scotland and Northern Ireland

The North of Scotland Hydro-Electric Board introduced andard tariffs in 1948 throughout its area. So far as domestic nsumers are concerned the tariff is a variable-block tariff of e three-block type with the assessment based on the number of bitable rooms. The term "habitable room" is defined as cluding every room in or connected with the premises except bathroom, lavatory, pantry, scullery, cloakroom, cellar, landing passage.

The Electricity Board for Northern Ireland has several tariffs ailable for domestic consumers, one of which is a two-part riff with fixed charge based on the floor area of the premises. r this purpose floor area includes all buildings concerned and measured externally.

The main domestic tariff of the Belfast Electricity Undertaking a two-part tariff with fixed charge based on rateable value with ernative flat rates for lighting, radio, etc., and for heating, oking, etc. This follows the usual practice of most local-thority undertakings in Great Britain prior to vesting date.

The Londonderry Electricity Undertaking has an all-in mestic two-part tariff with fixed charge assessed on the number "apartments" (comprising dwelling rooms, kitchens and bed-oms, whether or not wired for electricity, and electrically-hted garages).

(4) INDUSTRIAL TARIFFS

Experience over the years has shown that loads with a high ersity, such as those of small industrial consumers and other lustrial consumers with abnormally low load-factors, are best ered for by block or flat-rate tariffs, and that the larger con-ners are more appropriately catered for by some form of two-t tariff.

(4.1) Industrial Tariffs at Vesting Date

The percentages of industrial consumers on the main types of published industrial tariffs available at vesting date are shown in Fig. 6, from which it will be seen that 58·6% of these industrial consumers were supplied on flat-rate tariffs, 24·8% on block tariffs and 15·7% on two-part tariffs. There were in addition some consumers supplied under special agreements.

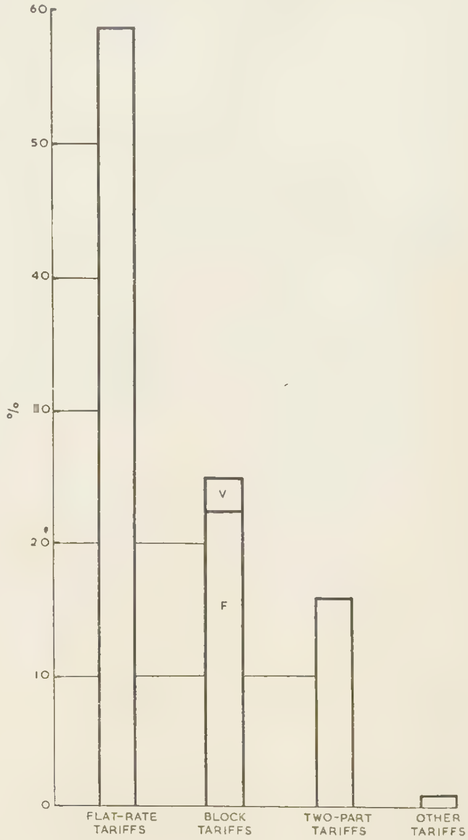


Fig. 6.—Industrial consumers supplied on the main types of tariff at 31st December, 1948, showing the numbers in each tariff group as a percentage of the total number of industrial consumers.

V—Variable-block tariffs.
F—Fixed-block tariffs.

It is appreciated that the number of consumers is not the best guide to the relative importance or magnitude of industrial supplies. The authors would also have liked to show in Fig. 6 the percentage consumption of each tariff group, but this information is not available for 1948.

(4.2) Industrial Tariffs Recommended

The Retail Tariffs Committee have recommended that, for consumers who take the whole of their electricity supplies from an Area Board, there should be two standard industrial tariffs, as follows:

(*a*) *For industrial consumers with an assessed demand of up to 50kVA.*

A variable-block tariff consisting of two or three blocks.

(*b*) *For industrial consumers with an assessed demand of 5kVA* or more.*

A two-part tariff with a maximum-demand charge and a running charge.

Tariffs (*a*) and (*b*) are alternative to each other over the range from 5kVA* to 50kVA of assessed demand.

* The lower limit of 5kVA may be removed altogether, subject to a minimum payment, if desired.

The size of the primary block of block tariffs should be based either on the assessed maximum demand or on the floor area, and the demand charge of two-part tariffs should be based on either the kilovolt-amperes of measured maximum demand, or kilowatts of measured maximum demand, with a recommendation to kilovolt-amperes. The maximum-demand charge should be on a monthly or annual basis at the option of each Area Board, and provision may be made for steps in the demand charge to allow for reduction of charges with magnitude of demand. There should be steps in the running charge related to load factor.

Demands taken during specified night hours in excess of those taken during the day-time should be supplied at a reduced charge, by agreement, where the load is large enough to justify the special metering equipment involved.

There should be a fuel cost variation clause associated with the running charge of two-part tariffs, but not with block tariffs. For high-voltage supplies the recommended fuel clause is as follows:

> The payment in respect of each month shall be subject to an addition or reduction at the rate of 0·0007d. per kilowatt-hour supplied in that month for each penny by which the fuel cost per ton used for the purpose of, and shown on, the invoice for the supply of electricity in bulk by the Central Electricity Authority to the Board in the previous month is more or less than 60s. 0d.

In the case of medium-voltage supplies, the recommended fuel cost adjustment is 0·00075d. instead of 0·0007d.

The above fuel clause is an improvement on the one used by the majority of former electricity undertakings—which clause was based on the average annual cost of fuel per ton and necessitated the rendering of supplementary accounts to consumers after the end of each year of supply; this method had the disadvantage that such supplementary accounts were often very much delayed by the time the cost of fuel had been finally ascertained for the year of account.

(4.3) Procedure for fixing Standard Industrial Tariffs

In order to obtain a clear picture of the effect of introducing standard tariffs in lieu of the multitude of industrial tariffs which were in operation at vesting date, it was necessary to make certain that the information on which calculations were to be based was correct to within very small limits of error.

The considerable numbers of small industrial consumers normally supplied from medium-voltage networks generally have no abnormal load characteristics, and the standard tariffs for these consumers could therefore be formulated by statistical sampling methods.

Larger industrial consumers, with demands of, say, 50 kVA and over, required more detailed treatment. These consumers comprise firms of various sizes whose individual electrical requirements represent a wide range of demands and load characteristics, and Area Boards were faced with the task of ensuring not only that any new tariff accurately reflected the costs incurred in supplying these consumers, but also that the tariffs would be equitable as between individual consumers over the whole range of load requirements and load factors.

Because of the number of factors to be considered when formulating standard tariffs for larger industrial consumers, the survey information had to be capable of easy segregation into a variety of groups to give a reliable basis for calculation of the monetary results for all the consumers affected, and it was generally found that a comprehensive individual survey was necessary.

One of the major problems was the monetary disturbance to consumers resulting from new tariff levels, and careful consideration was necessary to ensure that equitable treatment was afforded over the full range of demands and load factors. one Board's area the tariff calculations indicated that, whilst t overall average increase in revenue would be some 16%, whi increase was required to make industrial supplies econom some individual consumers would be involved in much grea disturbances.

Table 2 shows the average percentage monetary disturbance this Board's industrial consumers covered by the detailed surv with consumers grouped according to magnitude of demand.

Table 2

Maximum-demand groups	Number of consumers	Total energy supplied	Average load factor	Average increase in charges
kW		kWh	%	%
40–200	1 932	313 932 082	20·3	15·37
201–500	585	420 350 032	25·6	15·35
501–1 000	246	436 720 272	29·0	17·12
1 001–5 000	151	822 642 378	34·8	16·8
Total ..	2 914	1 993 644 764	28·3	16·28

This analysis indicated that within very small limits t increased charges would be spread more or less equally over t groups of consumers of varying sizes.

Table 3 shows a further analysis of the same consume grouped into those with load factors up to 27% and those wi higher load factors, which gives a very different picture.

Table 3

Category	Maximum-demand groups	Number of consumers	Total energy supplied	Average load factor	Avera increa in charg
	kW		kWh	%	%
Category A	40–200	1 673	226 953 735	17·2	19·7
Consumers with	201–500	420	220 008 114	19·3	23·2
load factors of	501–1 000	144	175 464 724	19·8	30·1
up to 27%	1 001–5 000	71	206 380 286	20·2	35·0
	Total ..	2 308	828 806 859	19·0	26·0
Category B	40–200	259	86 978 347	38·0	0·7
Consumers with	201–500	165	200 341 918	40·3	4·7
load factors	501–1 000	102	261 255 548	41·9	6·9
above 27%	1 001–5 000	80	616 262 092	45·9	9·7
	Total ..	606	1 164 837 905	43·3	7·4
	Grand Total	2 914	1 993 644 764	28·3	16·2

An examination was made as to the practicability of reduci the disturbance to the lower-load-factor consumers, but it w found that to obtain approximately equal percentage increases f Categories A and B it would be necessary to reduce the maximu demand charge by up to 45% and to increase the running char by some 54%. This would have produced a tariff which, whi favouring the lower-load-factor consumer, would have be unduly burdensome to the higher-load-factor consumer.

Moreover, in the course of time the effect of such a tar might well be that many of the higher-load-factor consume would find it more advantageous to install their own plant, whi would mean the loss to the Board of this high-load-fact revenue followed by inevitable increases in tariffs, the net resu being that in the end neither the Board nor its industrial co sumers would secure any benefit from such a tariff.

This examination showed that in the case of larger industr

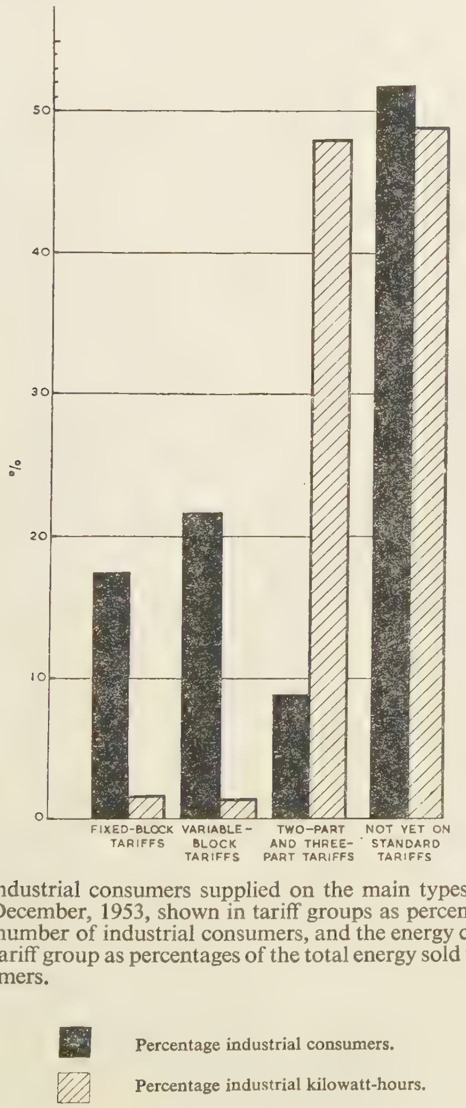
nsumers any such attempt to amend the values of the various mponents of the tariff in order to level out the monetary disbances could result in a tariff which would bear little relation costs and therefore could not be justified.

(4.4) Industrial Tariffs at the End of 1953

Of the nine Area Boards which have so far standardized their lustrial tariffs, each Board has introduced a tariff based on asured maximum demand, seven of which are two-part iffs and two of which are three-part tariffs. The structure these tariffs varies between Boards, but it must be borne in nd that in the initial introduction of standard industrial tariffs questions of safeguarding Boards' revenues and limiting the turbance to consumers' accounts have been paramount and ne consideration has had to be given to the types of industrial iffs in force prior to vesting date. The authors' views are t, once this initial problem has been surmounted, the structures the various Boards' industrial tariffs will tend to come more d more into line with each other over the years.

Most Boards have provided block tariffs for the small industrial nsumer, but some of these take the form of fixed-block tariffs her than the variable basis recommended by the Retail riffs Committee.

Fig. 7 shows the percentage of industrial consumers on the main types of tariffs at 31st December, 1953, and also the relative percentage consumption for each type of tariff.



7.—Industrial consumers supplied on the main types of tariff at 31st December, 1953, shown in tariff groups as percentages of the total number of industrial consumers, and the energy consumed in each tariff group as percentages of the total energy sold to industrial consumers.

It will be seen that 17·6% of the total industrial consumers are on fixed-block tariffs consuming only 1·8% of the total industrial energy sold, 21·7% are supplied on variable-block tariffs consuming only 1·3% of the total, whereas only 8·9% of consumers are supplied on two-part or three-part tariffs based on measured maximum demand but consume 48% of the total energy sold. The number of consumers not yet on standard tariffs will steadily decrease as other Area Boards introduce standard tariffs, and also as existing special agreements reach termination dates.

(4.5) Experience in introducing Standard Industrial Tariffs

In making their recommendation that industrial block tariffs should be of the variable type with the size of the primary block based on assessed demand or floor area, the Retail Tariffs Committee were setting aside the majority practice in the supply industry for many years past. Most of the former electricity undertakings supplied their smaller industrial consumers on flat-rate or fixed-block tariffs, and, as a result, most Area Boards have found it very difficult to introduce a variable element into their industrial block tariffs. The authors consider that, provided industrial block tariffs are used to supply only those consumers whose main use is for motive power, there is little risk in offering a fixed-block tariff, bearing in mind the high diversity between the loads of the smaller industrial consumers to whom the block tariff mainly applies.

A further important point which has come to light during the introduction of standard maximum-demand tariffs for industrial consumers is the need to fix a ceiling for the average price to be paid for such supplies. If this is not done maximum-demand two-part tariffs can, in cases of very low load-factors, result in the payment of unduly high average prices. The use of a ceiling price is comparable to the offering of a fixed-block tariff and can be justified for the same reasons. In fact one way of providing a limiting price is to offer a fixed-block tariff as an alternative to the maximum-demand two-part tariff to all industrial consumers whose usage is predominantly for power, and not only to those whose assessed demand does not exceed 50kVA (as recommended by the Retail Tariffs Committee).

(4.6) Method of Levying Maximum-Demand Charge

It is not proposed to describe here the relative merits of apparent power and active power for the measurement of chargeable maximum-demand because, when the whole subject is examined carefully, there is little to choose between the two methods.

There remain for consideration, however, the important questions whether the measurement of chargeable maximum demand should be confined to certain hours of the day as in the Central Electricity Authority's present bulk-supply tariff and whether it should also be confined to the four winter months (November–February) during which the system demand usually occurs.

Where the maximum-demand is charged on an annual (as against monthly) basis, the authors consider that upon request from consumers the full demand charge should be levied only on demands registered during the peak hours (7.0 a.m. to 6.0 p.m. or such hours as may suit the load curves of individual Area Boards) from Mondays to Fridays inclusive, with a lower demand charge for excess demands registered outside these hours and/or days (Saturday mornings can reasonably be excluded from the peak-hour period for such time as industry operates a five-day week).

Such arrangements need not necessarily be included in

published standard tariffs on account of the complication to metering, but should be freely available on request. The consumers concerned may be called upon to pay a rental for, or the cost of, the additional metering equipment involved.

As the system maximum demand of an Area Board will occur during the peak hours of the four winter months, the full annual demand charge must be levied on consumers' demands incurred during these peak hours and months, but there is justification for a lower charge for excess demands set up outside the four winter months even bearing in mind the decrease in plant availability during the summer owing to annual overhauls.

Where supplies are taken on a monthly tariff the demand charges can only be levied on the maximum demand set up in each month of account.

Where consumers can arrange the processes at their works so that the highest demand is taken outside the normal day hours, the excess demand recorded during night hours should be charged at a lower rate on similar lines to the principle employed for annual tariffs.

(4.7) Standby Supplies

It has not been found possible for Boards to lay down any hard and fast rules for tariffs for standby supplies in the event of the breakdown of consumers' private plant, because so much depends on individual circumstances. If a consumer is taking a substantial part of his power requirements from an Area Board the latter may be able to provide a standby supply on more favourable terms than if the consumer normally supplied the whole of his requirements from his own private plant. In the former case there is some regular revenue coming in to help meet the costs of the distribution plant capacity reserved. In the latter case there is no such regular revenue and the Board must ensure that they get a proper return on the distribution plant capacity held in readiness for the consumer's use and that they are adequately safeguarded against any maximum-demand charges they may incur for the bulk supply.

Where a consumer normally supplies the whole of his power requirements from a private plant and requires a supply from the Board for standby purposes only, the charges to the consumer would generally be as follows:

(*a*) The capital cost of the connection to the nearest existing distribution point suitable for affording the standby supply.

(*b*) An annual fixed charge in respect of the distribution capacity reserved.

(*c*) For supplies actually taken:

(i) The monthly demand charge in the normal standard tariff, less one-twelfth of the charge under (*b*) above, a demand charge at the rate of four times the resultant monthly demand charge being made in respect of the maximum demand taken at any time during the four winter months, and a demand charge at the resultant monthly rate being made in respect of the demands taken during the remaining eight months of the year.

(ii) The running charge in the normal standard tariff (with fuel cost adjustment).

Standby tariffs along these lines are in operation in the areas of a number of Boards.

A weakness of this basis for purely standby supplies is that the charging of four times the monthly demand charge for a maximum demand registered at any time in the four winter months does not offer the consumer any incentive to get his plant back into commission quickly once it has broken down.

If, on the incidence of a breakdown in a winter month, the consumer is committed to paying four months' demand charge he may tend to take his time in repairing his plant and may even carry out a major overhaul, thereby worsening the cumulative effect of breakdown standby supplies.

The longer a breakdown supply is taken from a Board's system, the greater is the risk to the Board of being involve a heavy maximum demand charge for the bulk supply fo full year.

Some method of relating the demand charges for stan supplies taken to the actual duration of breakdown in the wi months appears worthy of consideration.

The many diverse cases of supplementary supplies are dealt with in the paper. The situation is complicated by fact that, according to the load characteristics or other circ stances, some industrial supplies are afforded on mon maximum-demand tariffs and others on annual maxim demand tariffs, and these factors will influence the actual fo of tariff offered for supplementary supplies.

(5) COMMERCIAL TARIFFS

The commercial group, representing in the aggregate so 1·25 million consumers, covers an extremely wide and va range of consumer classifications.

Commercial tariffs have to be designed to cater for practic all supplies other than those afforded under domestic, indust or farm tariffs, and therefore in addition to the purely commer consumers such as shops, offices, etc., have also to embrace many other consumer classes such as hospitals, schools, colle public buildings, places of worship, clubs and other types premises.

Except in special cases, commercial consumers have one th in common, namely that lighting constitutes a high proport of their load.

(5.1) Commercial Tariffs at Vesting Date

The percentages of consumers on the main types of commer tariff available at vesting date are shown in Fig. 8, from whic will be seen that the majority (49·3%) were supplied on flat ra 27·6% on two-part tariffs and 21·55% on block tariffs.

It is of interest to note the variety of bases of assessment two-part and variable-block tariffs.

(5.2) Commercial Tariffs Recommended

The Retail Tariffs Committee recommendations for commer tariffs were identical with those for industrial tariffs, as set in Section 4.2, except that in the case of commercial two-p tariffs the maximum-demand charge should preferably be on annual basis, and in the case of commercial block tariffs charges should reflect, as far as practicable, broad differences load characteristics between different classes of consumer.

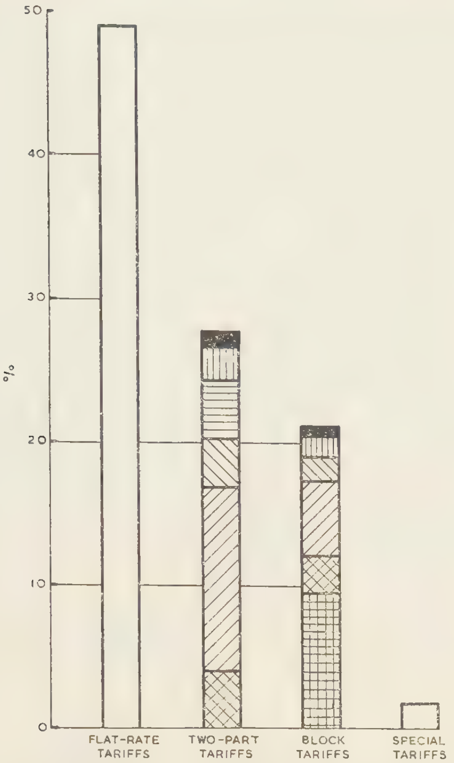
(5.3) Procedure for Fixing Standard Commercial Tariffs

The procedure for fixing standard commercial maximu demand tariffs has generally been the same as that adopted industrial maximum-demand tariffs, but it may be of interest describe the method used by one Board to formulate a commer block tariff based on floor area.

It was clear that more than one rate of floor-area assessm would be necessary to cover the range of premises concern It was thought at first that two different rates of assessm would suffice, and trial calculations were made on a small se tion of several hundred consumers using a number of varia block tariffs of the two-block type. It was found, however, t the monetary disturbance was too great and that further rates floor-area assessment would be necessary; also that the introd tion of a fairly large intermediate block of energy at a p around the average price expected from these supplies tended reduce the disturbance and make for a more balanced tariff.

A tariff incorporating these amendments was therefore form lated and the revenue from all the consumers was calculated.

In order to study the effect of this revised tariff on the differ



8.—Commercial consumers supplied on the main types of tariff at 1st April, 1948, shown as percentages of the total number of commercial consumers.

Size of premises. Measured maximum demand.
Rateable value. Other bases.
Total installed load. Fixed-block tariffs.
Installed lighting load.

ses of commercial consumer the revenue calculations were : compiled in seven consumer classifications, but further mination of the returns showed that the separate rates of essment could be cut down to four, as follows:

Rate A.—Shops, offices, surgeries, restaurants, places of enter-inment and similar premises.
Rate B.—Hotels, boarding houses, public houses, clubs and similar emises; also industrial premises in which the supply is taken ainly for lighting purposes, warehouses and garages.
Rate C.—Hospitals, schools, public buildings and similar premises.
Rate D.—Churches and other places of worship.

t each stage of the calculations the monetary disturbance to sumers was studied on a percentage basis as set out in the owing typical example:

Percentage Monetary Disturbance	*Percentage of Consumers affected*				
Exceeding 100	2·3				
Exceeding 50 and up to 100	9·8				
Exceeding 30 and up to 50	8·3				
Exceeding 20 and up to 30	10·5				
Exceeding 10 and up to 20	10·5				
Up to 10	18·8				
		33·9	58·0	72·1	87·2
Up to 10	15·1				
Exceeding 10 and up to 20	13·6				
Exceeding 20 and up to 30	3·6				
Exceeding 30 and up to 50	6·8				
Exceeding 50	0·7				

The above method shows clearly the percentage of consumers in each disturbance "band" and also the percentage of consumers falling into each plus and minus range, i.e. ±10%, ±20%, etc.

(5.4) Commercial Tariffs at the End of 1953

Eleven Area Boards have so far standardized their commercial tariffs; the majority have introduced two-part or three-part tariffs based on measured maximum demand, and have also adopted one or more other standard tariffs to cater for the varied range of commercial consumers in their respective areas.

The other standard tariffs comprise variable-block tariffs based on floor area, maximum power requested or installed load, fixed-block tariffs and flat rates. The picture at the end of 1953 is shown in Fig. 9, from which it will be seen that 67·9% of commercial consumers are now supplied on standard tariffs. It is of interest to note that 47·2% are supplied on variable-block tariffs, and that measured maximum-demand tariffs now cater for only 0·6% of the number of consumers.

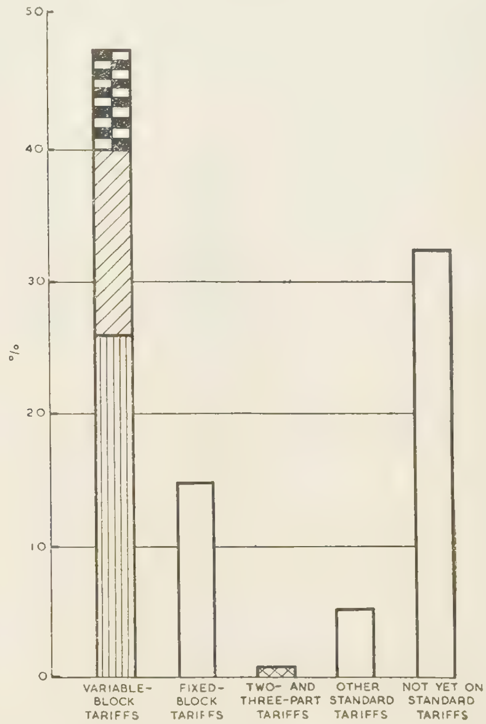


Fig. 9.—Commercial consumers supplied on the main types of tariff at 31st December, 1953, shown as percentages of the total number of commercial consumers.

Maximum power required.
Installed load.
Floor area.
Measured maximum demand.

(5.5) Experience in introducing Standard Commercial Tariffs

The authors are of the opinion that the use of assessed demand as the basis for determining the fixed charge of commercial two-part tariffs or the primary block of commercial variable-block tariffs has the disadvantage that it is difficult to keep the assessments up to date without regular visits to consumers' premises.

The floor-area basis of assessment appears to be the more appropriate, provided different rates of assessment are introduced to take account of the magnitude of demand and consumption of electricity relative to a given floor area. Experience has shown that to label all consumers in this category as "commercial" and to place them on the same basis of assessment is unrealistic, since there is a great difference between the average use of electricity for a given floor area in the case of, say, a shop which usually has a high intensity of lighting, and a church or village hall where the intensity of lighting is generally very much lower. Similarly, premises such as hotels, clubs, boarding houses, etc., which have a substantial amount of residential accommodation, require different treatment.

Although the measurement of floor area is troublesome in the first instance, it is easier to apply to commercial premises than to domestic premises for the reason that the number of commercial premises is comparatively small and the rate of connection of new premises is low, so that the problem of initial assessment is not so formidable.

Floor-area measurements, once obtained, are more stable than any other basis of assessment and do not necessitate periodic checking. The few cases of structural additions to existing buildings can easily be dealt with as a matter of routine.

Although it was the intention of the Retail Tariffs Committee that Area Boards should discontinue the previous practice of quoting flat-rate tariffs for lighting and for other purposes as alternatives to two-part or block tariffs, the authors consider that in order to limit the increased charges which individual consumers may have to pay on the introduction of standard tariffs, it may be necessary to retain flat rates for the time being.

The necessity for flat-rate tariffs will, however, decrease year by year as the utilization of electricity for all purposes becomes general, and this should lead to their eventual disappearance.

(5.6) Commercial Catering Supplies

There is a large potential demand for electricity in the commercial catering field, and although some pre-vesting-date undertakings built up this load to a considerable extent, and several Boards have since done so, the market is still largely undeveloped. The authors have in mind particularly such loads as kitchens in schools, cafés and hotels, etc., fish-frying ranges, and the variety of bakers' ovens, all of which are of great value in helping to fill up valleys in Area Boards' load curves.

The amount of business which can be obtained depends very largely on the tariff offered and the form of tariff is particularly important. Although some commercial catering establishments have fairly good load factors, this does not apply generally, and in many cases the maximum-demand tariff is unsuitable. In any event, with such a competitive business, it is essential to have a simple tariff which is easily understood. Fortunately, considering the load as a whole, there is considerable diversity between the different applications. Fig. 10 shows four load diagrams of typical commercial catering installations and indicates the kind of diversity and the character of much of the commercial catering load.

Load diagram (*a*) is for a typical fish-frying installation. In this case frying is carried out at midday as well as in the evening, but it must be borne in mind that many fish-frying ranges are not used on any day until after 7.0 p.m. Even in those cases where frying is carried out at midday it is not usually done on more than two or three days each week, one of which is a Saturday.

Load diagram (*b*) is for a typical bread bakery. The oven is on maximum load for an initial period which may be even earlier than shown in the diagram, and subsequently operates at a much lower load, except for short periods whilst the oven is being "peeled," when the load is temporarily increased.

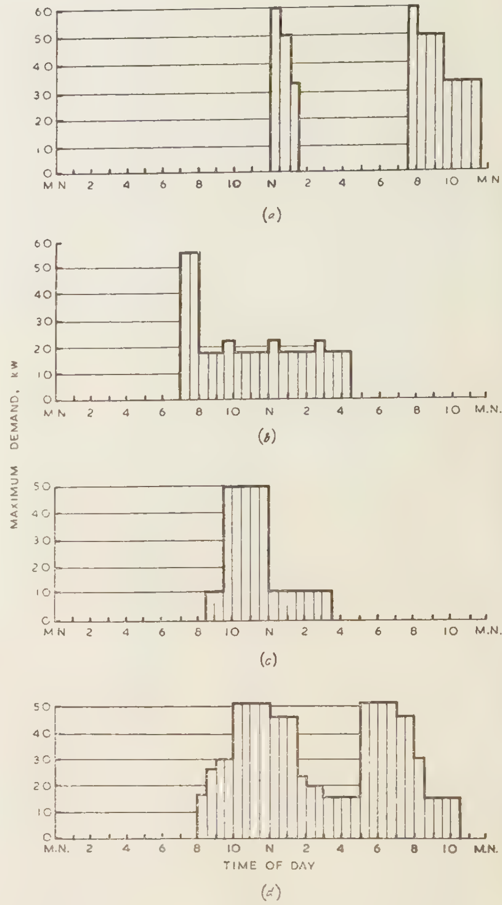


Fig. 10.—Load diagrams of typical commercial catering installati

(*a*)—Fish-frying installation. (*c*)—School kitchen.
(*b*)—Bakery. (*d*)—Restaurant.

Load diagrams (*c*) and (*d*) are for kitchens, each of differ types, the first cooking for a day school catering for mid meals only, and the second for a restaurant catering mainly midday and evening meals.

The most suitable forms of tariff are either a flat-rate tariff o block tariff in which there is only a small margin (say farthing) between the price per kilowatt-hour in the prim block and the follow-on rate.

(5.7) Commercial Tariffs in the North of Scotland and North Ireland

The commercial tariff of the North of Scotland Hydro-Elec Board is a variable-block tariff of the three-block type with assessment based on a combination of floor area and the load motors and special apparatus installed.

Several tariffs are available to commercial consumers in area of the Electricity Board for Northern Ireland, one of wh is a two-part tariff with fixed charge based on floor area. fixed-charge rate for shops, offices, etc., is three times that hotels, clubs, larger boarding houses and guest houses.

The main commercial tariff of the Belfast Electricity Un taking is a two-part tariff with the fixed charge based on rate value.

The Londonderry Electricity Undertaking has several diffe flat-rate tariffs available for different commercial uses and al block tariff of the two-block type with primary block assessed lighting maximum demand.

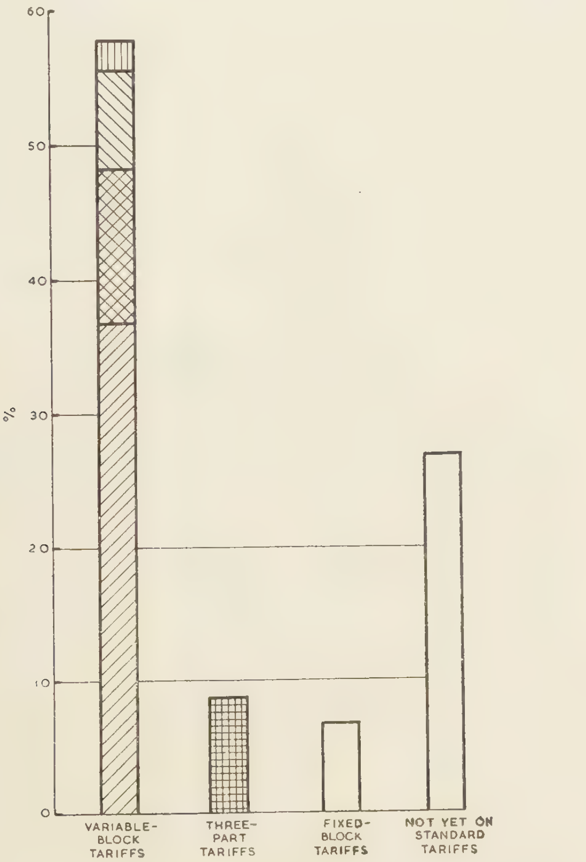
COMBINED DOMESTIC AND COMMERCIAL PREMISES

lthough the combined-premises class of consumer represents y 1·6% of the total number of consumers, it is nevertheless te an important class comprising some 230 000 consumers o use over 700 million kWh per annum.

There are no reliable national statistics available for the period to vesting date because of the variety of methods in operation charging these consumers. Some undertakings treated them wholly commercial, some treated the two sections of the mises as separate domestic and commercial premises, others ered a special combined premises tariff, whilst the remainder plied them on flat-rate or block tariffs.

The Retail Tariffs Committee recommendation was that comed premises should be assessed in accordance with the standard mestic tariff for the domestic part of the premises and in cordance with the standard commercial tariff for the comrcial part of the premises.

This recommendation has, in general, been followed by those ea Boards who have so far effected standardization, and . 11 shows the percentage of combined premises supplied on the main types of tariff at 31st December, 1953. It will be seen that approximately 73% of this consumer group is now supplied on standard tariffs and that the tariffs for 57·5% of the consumers are in accordance with the recommendations.



. 11.—Combined-premises consumers supplied on the main types of tariff at 31st December, 1953, shown as percentages of the total number of such consumers.

	Domestic section	*Commercial section*
▥	Floor area.	Floor area.
▧	Rooms.	Mixed bases.
▩	Rooms.	Installed load.
▨	Rooms.	Floor area.
▦	Floor area.	Assessed maximum demand.

(7) FARM TARIFFS

The divergence of opinion as to what constituted a farm, coupled with the differing treatments of farm supplies prior to vesting date, made it relatively more difficult to deal with this consumer group. Considerable research was necessary before a suitable tariff could be designed and in some Board areas investigations are still proceeding.

(7.1) **Farm Tariffs at Vesting Date**

Fig. 12, based on the statistics available at vesting date, shows the percentage of farm consumers supplied on the then available types of tariffs.

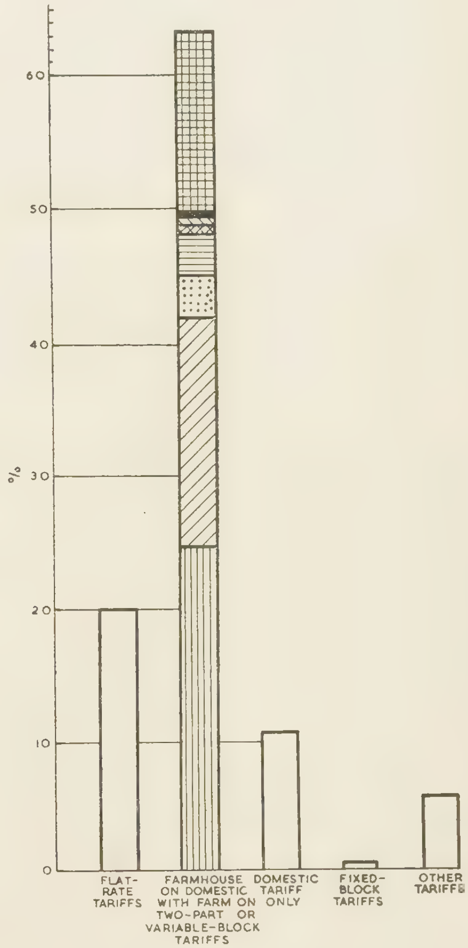


Fig. 12.—Farm consumers supplied on the main types of tariff at 1st April, 1948, shown as percentages of the total number of farm consumers.

Floor area.
Installed plant.
Rateable value.
Acreage.
Service capacity.
Capital expenditure.
Type of farm.
Other bases.

(7.2) Farm Tariffs Recommended

The Retail Tariffs Committee recommended that the appropriate basis for farm tariffs should be as follows:

Supplies to Farmhouses.

The tariff for domestic supplies provided to farmhouses and related cottages should correspond to the form of tariff adopted by each Area Board for rural domestic supplies.

Supplies to Farms for use outside the Farmhouse.

The tariff for supplies for farming purposes other than domestic supplies to the farmhouse and cottages should be of the same form as for the domestic supplies to the farmhouse except that the assessment of the fixed charge of a two-part tariff or the primary block of a block tariff should be based either on the assessed maximum demand or on the floor area.

It was recognized that special tariffs might have to be evolved for the development of off-peak loads such as summer and autumn crop-drying.

(7.3) Farm Tariffs at the End of 1953

Nine Area Boards have standardized their farm tariffs. Whilst all these Boards have applied their standard domestic tariff to the farmhouse, the farm premises component is related in four cases to installed load, and in the other cases to assessed demand, farm acreage, floor area of farm buildings, maximum power requested and transformer capacity respectively.

One Board has also provided as an alternative for both the farmhouse and farm premises a variable-block tariff based on maximum power requested.

Standardization has decreased the former variety of farm tariffs, and Fig. 13 shows the percentage of farm consumers supplied on the main types of tariff at 31st December, 1953.

Only 27·9% of farm consumers remain on non-standard tariffs. Of the 72·1% of farm consumers who are now supplied on standard tariffs the majority are on variable-block tariffs.

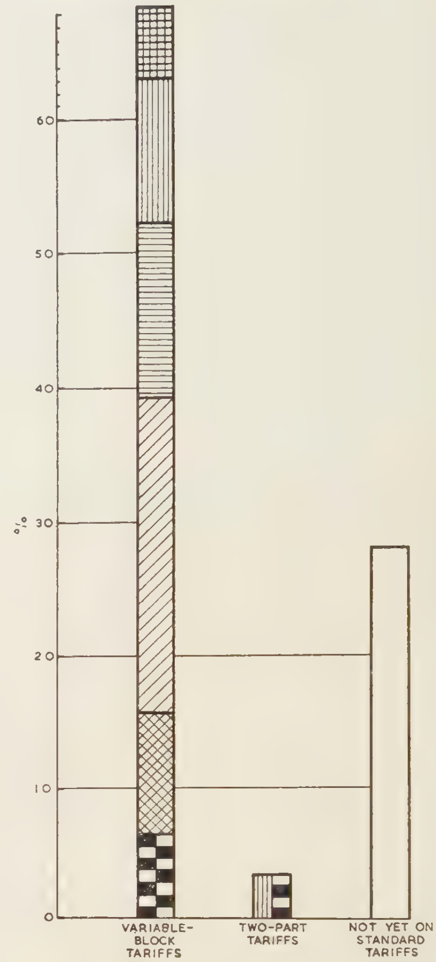


Fig. 13.—Farm consumers supplied on the main types of tariff at 31st December, 1953, shown as percentages of the total number of farm consumers.

	Farmhouse	Farm premises
	Rooms.	Transformer size.
	Rooms.	Floor area.
	Rooms.	Acreage.
	Rooms.	Installed load.
	Rooms.	Assessed demand.
	Maximum power required.	
	Floor area.	Maximum power required.

(7.4) Experience in introducing Standard Farm Tariffs

The same amount of experience has not yet been gained with standard farm tariffs as with domestic tariffs owing to the fact that only a few Area Boards have had their new farm tariffs in operation for any length of time. Neither of the two assessment bases recommended by the Retail Tariffs Committee are free from difficulties.

In the case of the floor-area assessment basis the following problems arise: (*a*) there is some doubt whether the assessment should include open-sided buildings such as cart sheds, Dutch barns, covered crewyards, etc., where sometimes as much electricity may be used as in totally enclosed buildings, and (*b*), a decision has to be made on how to deal with portable poultry houses and pig and poultry arks, bearing in mind that pig and poultry farms may use a considerable amount of electricity. Assessments based on permanent buildings only might place such farms at a distinct tariff advantage in comparison with other types of farm.

With the assessed-demand basis, there is the difficulty of keeping assessments up to date and the further disadvantage that a farmer's assessment has to be increased whenever a substantial amount of additional apparatus is installed.

These difficulties have resulted in Area Boards introducing farm-tariff structures which they consider best suited to the particular circumstances in their own areas of supply.

(7.5) Farm Tariffs in the North of Scotland and Northern Ireland

The farm tariff of the North of Scotland Hydro-Electric Board is a combination of the domestic (rooms) tariff for the farmhouse and the commercial (floor area and installed load) tariff for the farm buildings and agricultural apparatus. The first 20kW of agricultural apparatus is excluded from the installed load assessment.

Farms in the area of the Electricity Board for Northern Ireland are charged on a two-part tariff with fixed charge based on floor area for farm lighting and for domestic purposes. Motive power is separately metered and charged at power rates.

(8) RETAIL TARIFFS IN OTHER EUROPEAN COUNTRIES

Although the paper is concerned mainly with the tariff structures of the fourteen Area Boards, it may be of interest

ok at the practice in certain European countries which have lopted tariffs bearing some resemblance to those in Great :itain.

In Germany, Sweden, Finland, Switzerland and Belgium the incipal domestic tariff is a two-part or three-part tariff with sessment based on the number of rooms. In some cases, oms smaller than 6 m² to 8 m² are omitted and in other cases oms larger than about 25 m² attract an increased assessment. . Denmark a special committee recommended alternatives for e domestic tariff based either on rooms or floor area. Stan- ırdization has not yet progressed very far in France, but the ıris area of Électricité de France has a variable three-block omestic tariff with assessment based on the number of rooms. : most of these countries the definition of rooms is similar to at adopted by the Area Boards.

The standardization of industrial tariffs has not been effected any large extent on the Continent, but with regard to tariffs r commercial and similar premises a number of countries, cluding Sweden, Finland, Denmark and Belgium, have adopted vo-part or three-part tariffs for lighting, and sometimes for all ırposes, based on floor-area assessment. In general there are parate tariffs based on installed load for heating and power. ı all the cases examined the floor-area assessment is divided into ıtegories depending on the type of premises, the number of fferent rates of assessment varying from three in Germany ıd Belgium to seven in Denmark.

Farm tariffs in Germany, Sweden, Finland and Switzerland ıve an assessment based on the area of cultivated land so far as e farm use, as opposed to domestic use, is concerned. In ıme cases there is an additional assessment based on installed ad for motors. In Denmark the farms tariff assessment is ısed partly on the tax valuation of the property and partly on stalled load.

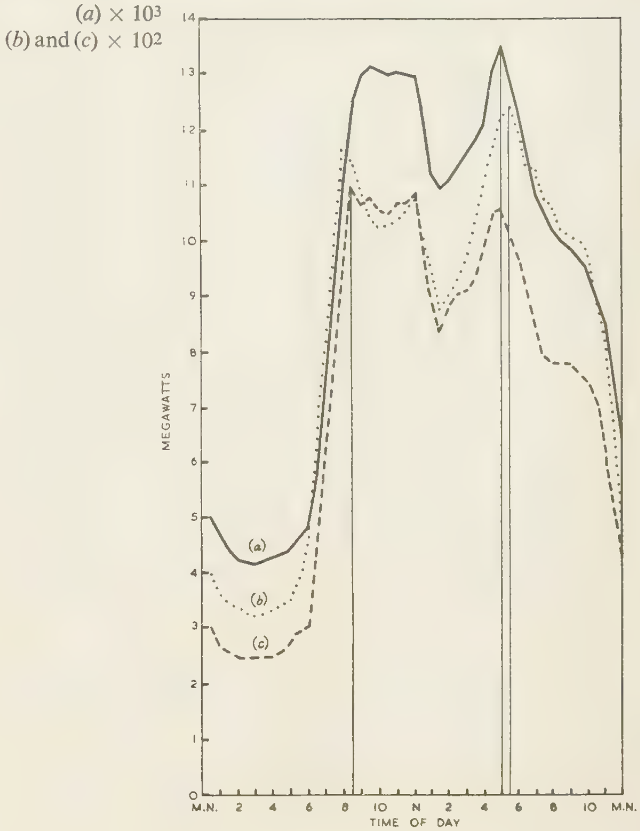


Fig. 14.—System load curves.

(a) National curve.
(b) and (c) Typical Area Board curves.

(9) RESTRICTED-HOUR TARIFFS

(9.1) Industrial and Commercial Supplies

The most satisfactory method of encouraging the off-peak use electricity is to offer a restricted-hour tariff which is available r apparatus connected to special circuits which are controlled such a way that electricity can be taken only during certain earranged hours. In the case of industrial and commercial pplies, the method of control usually presents no difficulty ıce the amount of energy used is generally large enough to sult in sufficient saving in costs to justify the provision of itable control-gear and time switches. The authors are not in vour of a two-rate or time-of-day tariff, because this allows ergy to be supplied at a low price between certain hours to paratus which has already registered a demand on the system peak hours.

1.1) Restricted Hours.

In determining the restricted hours for the purposes of these ecial tariffs two system load curves have to be considered: the national system load curve, and (b) the Area Board load rve.

The two may not be the same, as will be seen from Fig. 14, ich shows (a) the national system load curve for Tuesday, th December, 1952 (the day in the year 1952–53 when the ıximum demand on the Central Electricity Authority's system curred), and (b) and (c) typical load curves for two Area ards for the same year of supply. Curves b and c are for ednesday, 17th December, 1952, and Monday, 5th January, 53, respectively, the days on which the maximum demands of se two Boards occurred.

t will be seen that the national system peak occurred during the half-hour period ending at 5.0 p.m., whereas with one Area Board it occurred during the half-hour ending at 5.30 p.m., and with another the half-hour ending at 8.30 a.m.

Bearing in mind that Area Boards pay maximum-demand charges based on their own system peaks, the area load curve must be the main determining factor in fixing the restricted hours. Clearly, however, no Board should permit the use of electricity at off-peak terms during the national peak hours even if such use would not affect their own system peak. Looking at the national load curve it will be seen that off-peak terms can safely be offered between the hours from 6.0 p.m. to 7.0 a.m., which will probably also suit most Area Boards. It would not, however, be proper for Area Board (c) to offer supplies at off-peak terms during the afternoon national peak period simply because their chargeable maximum demand occurs during the morning. In any case, the difference in magnitude of load between the morning and afternoon peaks is usually so relatively small that restricted-hour supplies must be kept off both peak periods as the conditions may alter from year to year.

In addition to permitting restricted-hour supplies to be taken between 6.0 p.m. and 7.0 a.m. an afternoon "cut in" period should be allowed to enable a boost to be given to thermal-storage installations where necessary. This period will vary with different Area Boards, but it might well be from 12.30 p.m. to 3.30 p.m.

Some consumers will also wish to use their off-peak apparatus from noon on Saturdays to 7 a.m. on Mondays, and this should be permitted, though not necessarily included in published tariffs since it involves complication in control and is not required in all cases.

(9.1.2) **Principal Loads Suitable for Restricted-Hour Supplies.**

(*a*) *Thermal-Storage Heating and Battery Charging.*

These loads involve long-hour use of electricity and therefore warrant the quoting of a low charge per kilowatt-hour. The load is so important to the building-up of the system load factor, and consequently to the more efficient use of generating plant, that it should not carry the normal kilowatt-demand charge component of the usual industrial or commercial tariffs, although of course even an off-peak load attracts some capital and overhead charges.

The cost of installing a service—and often a special substation—to supply off-peak loads will have to be taken into account, however, and this may be done by means of a small periodic service charge or a capital contribution. Apart from this it is considered that the energy should be supplied at a flat-rate charge approximating to the unit charge of the standard industrial or commercial two-part tariff. This will be supplemented by a fuel-cost variation in the case of larger supplies, but for smaller supplies afforded at medium voltage the fuel-cost variation may, for convenience, be commuted at the current cost of fuel and the tariff reviewed from time to time if the fuel cost varies appreciably.

(*b*) *Flood-lighting, advertisement signs, etc.*

With this class of load the hours of use are usually very much shorter than with thermal-storage heating and battery charging, and such a low charge per kilowatt-hour is not justified. The authors feel that an appropriate tariff for electricity supplied to off-peak flood-lighting and advertisement signs, etc., would be a flat-rate charge at about mid-way between the price in the highest and lowest kilowatt-hour charges in the commercial block tariff (i.e. between 2d. and 3d. per kilowatt-hour at the present level of prices).

If costs of connection are considerable these would have to be covered either by a small periodic service charge or by a capital contribution.

(9.1.3) **Time Switches.**

It is important that time switches should be working accurately and such apparatus should therefore be provided and maintained by Area Boards. Consumers should pay a rental to cover the cost of providing and maintaining the time switches.

(9.2) **Domestic Supplies**

In the case of domestic consumers, the water heater is the only appliance in the normal household which inherently contains an element of thermal storage and which lends itself to the off-peak use of electricity. Immersion heaters, particularly, many of which are used in the warmer months only, are mainly an off-peak load and could be made entirely so, even in winter, if house builders could be persuaded to fit somewhat larger cylinders and to lag them.

Space heating by thermal storage may find application in some large houses, but the use will be very limited.

(9.2.1) **Cost of Control.**

It is difficult to offer off-peak terms for domestic water heating connected to special circuits because the cost of control more than offsets any tariff advantage that can be given to the consumer.

The water heater would have to be controlled by a synchronous-type time switch with spring reserve to ensure that the proper times of switching on and off were accurately kept and to ensure continuity of operation during short periods of interruption to the supply. An additional meter would also be required to measure the energy used on the separate circuit.

The approximate cost of this equipment, assuming that the time switches were purchased in bulk, would be:

	£	s.	d.
20 amp synchronous time-switch with spring reserve	9	10	0
20 amp single-phase meter	3	5	0
	£12	15	0

The annual costs would be:

	£	s.	d.
Annuity on £12 15s. 0d. for 15 years at 3¾% ..	1	2	6
Maintenance of time switch and meter		15	0
	£1	17	6

which would have to be charged to the consumer in the form of a rental.

It would be difficult to justify a domestic off-peak rate lower than ¾d./kWh with the follow-on rate of the domestic tariff at 1d./kWh. With this reduction of only ¼d./kWh, the off-peak consumption would have to equal 1 800 kWh per annum to extinguish the rental of £1 17s. 6d. and a further 960 kWh would have to be purchased before the consumer would save £1 per annum compared with the normal tariff. Since few domestic consumers use more than 2 MWh per annum for water heating, the expense of controlling water-heating circuits by time switches can hardly be justified.

(9.2.2) **Reduced Follow-on Rate in Domestic Block Tariffs.**

Though not strictly within the scope of restricted-hour tariffs, the most practicable method of encouraging the water-heating load may be to reduce the follow-on rate of domestic two-block tariffs after reaching a consumption level which would cover normal use for lighting, cooking, radio, television, irons, kettles, etc., and occasional space heating. For example, supposing the domestic block tariff consisted of a primary block at 5d./kW and a follow-on rate of 1d./kWh, the latter might be reduced to ¾d./kWh after the consumption had reached, say, 1·5 to 2 MWh per quarter. This would encourage water heating, which, as already indicated, is largely an off-peak load.

(10) CONCLUSIONS

The formidable task of standardizing tariffs by the fourteen Area Boards is well under way, but even when complete the tariffs will need to be constantly under review.

There are those who would criticize the recommendations of the Retail Tariffs Committee on the grounds that they were not sufficiently definite, but the authors do not share this opinion. Widely differing views on the subject of tariffs have been held in the supply industry for the last 50 years, and it was not to be expected that these could suddenly be reconciled at vesting date—in fact to do so would probably have meant rejecting some ideas of merit and thus stultifying ultimate progress; there is always a risk of this in any large-scale scheme of standardization.

An immense simplification of retail tariff structures has already been achieved, and even if this had resulted in uniform tariffs only within the area of each separate Board, it would have represented a very big advance over the multiplicity of tariffs in use by the former 541 undertakings. The progress is much better than this, however, because the tariffs of some of the Area Boards are very similar, thus achieving a larger measure of standardization.

Once Area Boards have overcome the initial hurdle of introducing their own standard tariff structures with the least disturbance to individual consumers' accounts, they will be able to examine the tariffs of neighbouring Boards whenever their own are due for review and thus endeavour to bring their tariffs more into line with those of their neighbours. This process will

esult in the progressive ironing out of small tariff differences etween Boards.

The authors consider that for domestic consumers, and also or small commercial and industrial consumers, the block tariff ; preferable to the two-part tariff as it is more easily understood y consumers and will eventually remove the need for an alter-ative flat-rate tariff to limit the price per kilowatt-hour for mall users. Present Continental practice favours two-part or nree-part tariffs, but where these tariffs are used one or more lternative tariffs are offered for small users.

The most interesting feature of the Continental tariffs is the asis of assessment generally chosen for domestic and com-nercial consumers. The rooms basis is undoubtedly the most opular for domestic consumers, and for commercial supplies ne assessment is usually based on floor area or installed load. Vhere floor area is used the range of premises concerned is sually divided into a number of groups depending on the eneral standard of illumination involved, and this procedure nes up with that followed by several of the Area Boards.

Once the initial change-over to standard tariffs has been com-leted and provided the present trend of increasing use of lectrical appliances continues, the authors are of the opinion hat fixed-block tariffs will be more widely adopted for domestic, arm, small industrial and commercial consumers. Abolition of he need for assessment and the simpler accountancy afforded y fixed-block tariffs will tend to outweigh the advantage of ariable-block tariffs in the matter of closer relationship between lectrical load and the fixed charge or primary block assessment.

With regard to maximum-demand tariffs, it is fairly certain hat there will be a general move towards a closer relationship f the demand and energy charges in such tariffs to the fixed and ariable components of the costs of affording supply. This will esult in simplified tariffs and may eventually avoid the necessity or steps in running charges related to load factor.

(11) ACKNOWLEDGMENTS

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The views expressed in the paper are not necessarily those of ither the Central Electricity Authority or any individual Area oard.

(12) APPENDIX

(12.1) Glossary of Terms

Installed Load.—The sum of the rated inputs of the consuming pparatus installed on a consumer's premises for connection to ne electricity supply system.

Service Charge.—A charge per consumer, levied once or eriodically, which is independent of the amount of electricity ctually supplied, but is usually related to the capital cost of naking the supply available to the consumer.

Fixed Charge.—A charge appertaining to a prescribed period of supply but independent of the number of kilowatt-hours supplied and of fluctuations in the demand. It is usually based on the size of the premises or on the capacity of the apparatus installed.

Demand Charge.—A charge appertaining to a prescribed period of supply based on the maximum demand in kilowatts or kilovolt-amperes.

Standing Charge.—A general term covering fixed charge and demand charge.

Running Charge.—A charge per kilowatt-hour supplied.

Fuel-Cost Variation.—A variation of the charge per kilowatt-hour based on the cost, and frequently, the calorific value of the fuel consumed at a group of generating stations.

Flat-Rate Tariff.—A tariff comprising a single charge propor-tional to the number of kilowatt-hours supplied.

Two-Part Tariff.—A tariff comprising a standing charge and a running charge.

Three-Part Tariff.—A tariff comprising a service charge, a standing charge and a running charge.

Maximum Demand Tariff.—A two-part tariff comprising a kilowatt or kilovolt-ampere charge and a running charge.

Fixed-Block Tariff.—A tariff in which the price is based on a diminishing series of rates per kilowatt-hour, applying to succes-sive blocks (of fixed size) of kilowatt-hours supplied during a prescribed period.

Variable-Block Tariff.—A tariff similar in form to a fixed-block tariff but in which the sizes of the blocks are variable, usually according to the maximum demand, the installed load, or the size of the premises. In the paper such tariffs are mainly of the two-block or three-block type.

Primary Rate.—The price per kilowatt-hour in the primary block of a block tariff.

Follow-on Rate.—The price per kilowatt-hour in the final block of a block tariff. For example, a two-block tariff has a primary rate and follow-on rate, and a three-block tariff has a primary rate, secondary rate and follow-on rate.

Two-Rate Tariff (Time-of-Day Tariff).—A tariff in which there are different costs for electricity used at different times of the day.

Restricted-Hour Tariff.—A tariff for a supply of electricity which is available only outside prescribed hours.

All-in Tariff.—A tariff making no distinction between the purposes for which the supply is used.

Load Factor.—The ratio of the number of kilowatt-hours supplied during a given period to the number that would have been supplied had the maximum demand been maintained throughout that period—usually expressed as a percentage.

Diversity.—Appertaining to "load diversity" in a general sense; the measure of diversity is "diversity factor," or the ratio of the sum of the maximum loads of individual consumers to the maximum load incurred by the same consumers at a supply point during simultaneous periods.

Peak, Peak Hours, Peak Period.—A period of the day when the maximum demand on an electricity supply system is likely to occur.

Area Board.—One of the fourteen Area Boards set up under the Electricity Act, 1947.

Note.—A number of the above definitions are based on those in B.S. 205: 1943, but some alterations have been made.

DISCUSSION BEFORE A JOINT MEETING OF THE SUPPLY AND UTILIZATION SECTIONS, 17TH MARCH, 1955

Mr. C. T. Melling: Under the Electricity Act, 1947, it is one of the duties of Area Boards to "promote the simplification and standardization of methods of charge. . . ." This is not the same as "to simplify and standardize tariffs," which implies money content as well as structure. To "promote the simplification and standardization of methods of charge" is a very general requirement. The Act does not state that methods of charge shall be standardized throughout the country, or, indeed, throughout the whole area of an Area Board; nor does it stipulate whether a consumer shall have the availability of only one standard tariff or whether he shall have the choice of several standard tariffs. It allows an Area Board to charge for supplies under an agreement as distinct from the tariff, and no stipulation is made about the relation which the terms under such an agreement shall bear to a standard tariff applicable to a similar consumer, or the relation which the standard tariffs shall bear one to another. The principal guidance in the Act—and this is a definite requirement—is that an Area Board shall not show undue preference in fixing tariffs and making agreements.

The industry's tariff policies and practices which the new organization inherited from its predecessors were generally good and consumers had undoubtedly benefited. The problem was therefore to examine these policies and practices, to retain what was good, to improve where possible and to evolve a general pattern which would produce equity and at the same time allow a desirable degree of experimentation for the further benefit of consumers.

But does "equity" mean that one consumer shall pay no more than another for a similar service of electricity, or does it mean that each shall pay a price in proportion to the cost of providing that similar service? Shall a preference—though not, of course, an undue preference—be shown in order to develop a load which will improve load factor and hence improve the economy of the industry to the further benefit of consumers?

These and many similar questions are inherent in any discussion on the standardization of tariff structures. The authors stress the importance of ensuring that standardization causes as little disturbance as possible to consumers, and they show in relation to domestic and other tariffs the average percentage increase or decrease for various categories of consumer. I do not agree that limitation of disturbance is "paramount," although I think it important. In relation to domestic tariffs, which cover by far the largest number of consumers, this problem of avoiding disturbance is certainly important and it was for this, among other reasons, that the Eastern Board decided to adopt a two-part tariff based on floor area: 85% of domestic consumers were already supplied on a two-part tariff and 70% of these were already assessed in accordance with floor area. There is no one perfect domestic tariff or basis of assessment, but in my opinion the two-part tariff has less disadvantages than the block tariff and has served the industry well for very many years. Similarly, the floor-area basis seems to provide less anomalies and difficulties than the rooms basis judging by relative freedom from complaint of the floor-area basis compared with the difficulties which seem to have been encountered in some parts of the country on that fine line of definition between scullery and kitchen.

Table 1 of the paper shows that the average consumption is very similar for houses up to and including four assessable rooms, and that it is only for the larger houses that there is a sharp increase in consumption. This same characteristic applies to the floor-area tariff, and Fig. A shows the results of a sample of domestic consumers each using more than 100 kWh per annum, i.e. consumers who would generally use the two-part

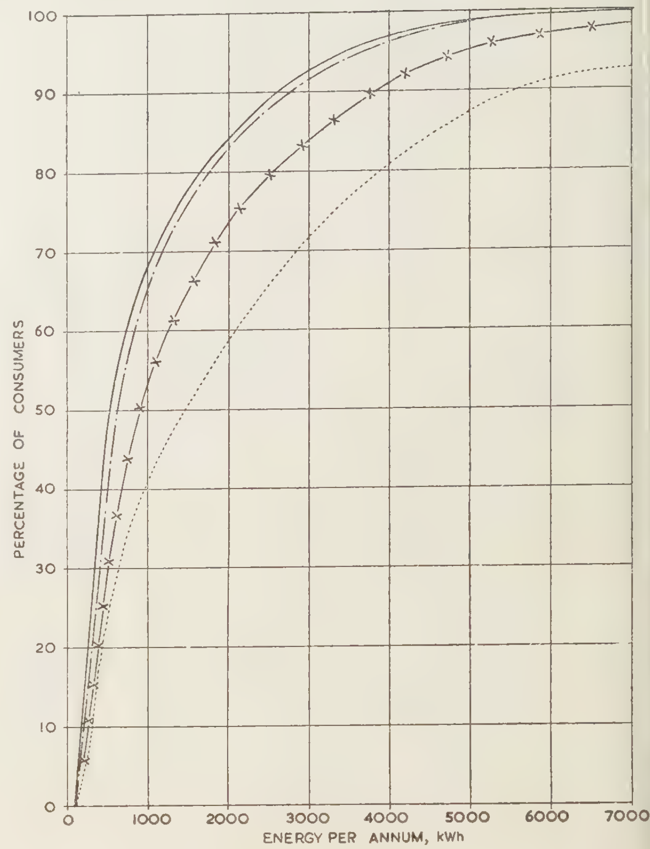

Fig. A.—Sample of domestic consumers using more than 100 kWh per annum.

0–799
800–1 199
1 200–1 599
1 600–1 999

tariff in preference to the alternative tariff for small consumptions. There is practically no difference in the average consumption of such consumers in houses up to 800 ft^2 and that of 800–1 200 ft^2. My own Board therefore adopted 1 200 ft^2 as the minimum assessable floor area, and this has the advantage that normal council houses, which are allocated to consumers rather than chosen by them, are all assessed at the same fixed charge.

On the commercial tariff the difference between the assessed demand and the floor-area basis is not absolute, but places commercial consumers at a different point between the domestic and the industrial. All Boards treat domestic consumers collectively by placing them in general groups, according to number of rooms or floor area, and in this respect they assume that every consumer is rightly treated if the collective treatment is correct, whereas in the industrial tariffs consumers are treated on an individual demand basis. Those who advocate the floor-area basis for commercial consumers are following the domestic procedure and grouping all commercial consumers with the same floor area together, irrespective of demand, whereas the others verge towards the industrial treatment of commercial consumers and treat them in accordance with demand. In time it may well be found that the two methods merge, by bringing down the industrial tariff to cover the larger number of commercial consumers and bringing up the domestic principle into the lower end of the commercial range.

The paper contains several opinions with which I do not agree, .g. the industrial tariff with no steps in the kilowatt-hour charge r the suggestion of a tertiary rate as a means of overcoming the eed for an off-peak rate.

On the matter of off-peak development the authors understimate the value of the night and day rate, which with a lownergy charge accompanied by a fixed charge, overcomes the ifficulty mentioned in Section 9.1.

The present stage of tariff standardization is an interim one. Much remains to be done before final steps can be taken, and is most desirable that there should be no undue haste in eaching the next stage, because we should resist any doctrinaire pproach. Let us think of the practical development of the ndustry and the great advances which have been made in the ast under conditions of tariff flexibility.

Mr. A. W. Jervis: With a subject of this nature there is a endency to justify the tariffs if one is on the supply side or to nake out a case for lower charges if one is associated with conumers. Since vesting day, Area Boards have done much to implify methods of charging, but in spite of the craving for tandardization, they should be more elastic in their classification f consumers.

The authors state that "commercial tariffs cover an exceedingly vide and varied range of consumer classifications." There is a ase for dividing this under more specialized headings, and taking realistic view of the supply problems and costs associated with ach section rather than covering under the same heading large tores, with load factors of 25–35%, and churches, with low oad-factors and all off-peak demand.

It has often seemed that some charges are formulated on the asis of "what the traffic will bear," for only thus can one justify he lower rates to industrial consumers, where (other than large sers) the average load factor is 15%, and the higher basic rates aid by commercial consumers with load factors of 30–50%.

I am surprised that the floor-area basis of assessment is put orward as acceptable for the future. I do not think any circumtances can justify this, except for very small consumers in single remises, for to bring about any equality must necessitate having large number of steps in the assessment.

Those who are formulating tariffs should not standardize urely for the sake of standardization. There seems at the noment some rigidity of outlook and a dislike of treating special ases individually. What was wrong in the past was not so nuch the multitude of tariffs but the wide range of costs. Cheap nergy in one area caused dissatisfaction in others. We still ave a legacy of this in the London area, where the divergence f prices paid is the greatest in the country. For this reason, to ntroduce systems of standardization must lead to a great deal f annoyance.

With all its faults, the fairest system of charging is the threeart maximum-demand tariff: reflecting as it does the actual cost f providing the supply, variation between consumers can always e satisfactorily justified without a feeling of bias towards one onsumer. Furthermore, variations in the cost of supply are utomatically adjusted and understood with the coal-clause riation. I appreciate that it has been difficult for the charges remain static during the testing period, but much annoyance being caused by the great number of increases being made. ong-term contracts should be re-introduced, so that consumers n have some feeling of stability over a period of years. Some enuine attempt should also be made to provide an ecoomical tariff for off-peak supplies, especially at night. The pportunity to increase usage has never been greater than it is esent.

Many other matters have not been touched which, although ainly technical, have become bound up with tariffs, e.g. high- or low-voltage metering, out-feeding rights from consumers' substations, etc. These could be dealt with more easily if less rigidity was shown in standardization.

Miss A. S. Lockhart: The Electrical Association for Women regards this question from the aspect of the consumer, and we feel it important, not only to avoid injustice, but to avoid the appearance of it. This remark is occasioned by Table 1. The authors have narrowed the effect of the new tariffs, but if they had considered 5- and 6-room houses in separate blocks, I think that they could have averaged out the decrease of 2% for 5-room houses and the increase of 3·2% for 6-room houses.

Might it be worth while, for the sake of goodwill, to give consideration to individual cases of hardship caused by changes in tariff, or to offer consumers the choice of the existing tariff or the new tariff for a short period?

With the new tariffs, the size of the block, the number of blocks and the energy charge may vary from place to place. Could the essential variation be applied by the addition or subtraction of pence in the shilling to the account as reckoned on a uniform tariff? Then one housewife would say, "I pay the standard tariff plus a penny in the shilling"; and another, "I pay the standard tariff less a farthing in the shilling." It will be argued that the first block has some relationship to capital charges, but this is a matter which concerns the cost accountant, and the final difference would probably not be very great. Incidentally, and regrettably, this would be a very easy means of introducing a coal clause to domestic consumers.

There is talk about domestic tariffs not rising as much as industrial rates. No one has suggested that the domestic consumers earlier paid too much, and there is no Federation of British Housewives to support her. The only advocate for the domestic consumer, apart from the E.A.W., is the Gas Council. I do not imagine that the E.A.W. will ever say "Thank goodness for gas," but it is a relief to know that there is a very active body which will be aware of what the electricity supply industry is doing, if it does it.

Much heat has been generated about village halls, partly because they all regard themselves, not as commercial, but as charitable institutions which should have a rebate on tariffs. At the Women's Institute debate on this subject one speaker feared that any concession would be paid for by someone else, and she preferred to put more money in the plate rather than pay for the electricity through her own tariff. I wonder, however, whether the village hall could not be regarded as a special sort of showroom for the electrical industry, which might lend domestic apparatus for display. The disadvantage that the village wash might be done in the village hall could be overcome by the ingenuity of the industry. This could avoid one of the objections to standardization of tariffs.

Mr. R. H. Rawll: In Section 10 the authors state that "widely differing views on the subject of tariffs have been held in the supply industry for the last 50 years, and it was not to be expected that these could suddenly be reconciled at vesting date." So far as engineers are concerned, I suggest that there will always be differences of opinion with respect to tariffs. I feel, however, that the general body of consumers throughout the country, and at least the supply industry, expected a greater measure of agreement to be achieved, for there were now only 14 or so electricity authorities dealing with the problem, whereas before nationalization there were more than 500. This is not to suggest, of course, that in all cases there should be complete standardization.

I therefore feel that in some respects the Retail Tariffs Committee were a little too timid and careful in their recommendations. For instance, in certain of these there are too many unnecessary alternatives. The average consumer no doubt fully appreciates the necessity that there should be differences in prices

between Area Boards, but surely, as regards the domestic tariff, he has a right to expect that the electricity supply industry has reached a stage when at least it could standardize on one method of charge. I certainly agree that there must still be a degree of flexibility in the form of the industrial, commercial and farm tariffs, but this seems hardly justified for domestic tariffs.

In this connection we find from Section 3.4 that, in 1953, of the three recommendations for domestic tariffs made by the Retail Tariffs Committee, the position was that a two-part tariff based on floor area had been taken up by two Boards, a variable-block tariff based on number of rooms was adopted by ten Boards and one Board had provided both of these tariffs, each based on the number of rooms. It would therefore seem from a consideration of these figures that, since such a comparatively high degree of standardization in the form of domestic tariffs has, in fact, resulted, the Committee would have been justified in putting forward a single recommendation without alternatives.

So far as commercial tariffs are concerned, it is stated in Section 5.4 that the majority of the Area Boards have introduced two-part or three-part tariffs based on measured maximum demands, but this has resulted in only 0·6% of the commercial consumers adopting this tariff. I wonder whether the authors can supply any reason for this.

In Section 9.22 the authors propose a reduction in the follow-on rate of domestic two-part tariffs might be made after the consumption had reached 1·5–2·0 MWh/quarter, in order to encourage the water-heating load. I imagine that this would also encourage consumption of supplies for all other purposes, including space heating.

Mr. E. W. Dorey: For the country as a whole the average price per kilowatt-hour sold for domestic supplies was 1·565d. in 1939 and 1·532d. in 1954, a reduction of 2%, whereas for industrial supplies the figures were 0·654d. in 1939 and 1·146d. in 1954. During these 15 years the price of fuel increased by 45s. per ton, equivalent to 0·43d. per kilowatt-hour sold; yet domestic charges fell by 0·033d. and industrial charges rose by 0·492d. It would seem that the burden of fuel increase is not being equitably distributed amongst these two classes of user, unless it can be shown that there has been a most remarkable reduction in cost of supply to the domestic user, owing to improved load-factor and decrease in related cost of distribution.

As evidence of what can happen, one Area Board announced in 1953 that the sudden rise in fuel price would cost the Board £1 200 000 per annum, of which one-half would be recovered under the fuel clause in industrial tariffs; charges to other classes of user were not to be increased, and it was hoped to recover the other half by a sales drive on off-peak supplies. The off-peak rate of 0·825d./kWh and the purchase cost without any overheads (but allowing losses in distribution) of 0·6d./kWh together leave a margin of 0·225d./kWh, and to make the £600 000 profit means off-peak sales of 620×10^6 kWh/annum, which is equal to 40% of the domestic supplies. I suggest that but a fraction will be so recovered.

We are told that a tariff should reflect accurately the cost of supply and be equitable over the whole range of load requirements and load factors. With this I agree, but find it difficult to understand why consideration should be given to the disturbance factor, since this can mean only a departure from an economic tariff to an expedient tariff; what generally happens is an increase to the high-load-factor user for the benefit of the low-load-factor user. Undue consideration of disturbance could account for the wide difference in the structures of industrial tariffs of the various Boards, whereas if tariffs were established on a sound economic basis, as envisaged by the authors, it should be possible to adopt a common structure of industrial tariffs in all Areas, any variations being confined to the monetary content varying in accordance with differing on-costs of distribution and percentage of kilowatt-hours sold to industry as a class.

The widely divergent tariffs existing in pre-vesting days, and continued under nationalization until published tariffs were introduced, can hardly encourage one to suppose that as a collection for any class they reflect the true cost of supply. As such, I feel that the disturbance factor should be completely ignored if the supply industry is to be established on a sound economic footing; this should reduce the wide differences in selling price per kilowatt-hour class by class and within classes which has been such an unsatisfactory feature of the industry for so many years and to a more limited extent still remains.

Mr. G. O. McLean: As one who took an active part in the discussions of the two last committees mentioned in Section 1.1, I am bitterly disappointed in this paper: it does not tell those of us who are in the supply industry a single thing that we did not know already. To those who are not in the industry, and particularly to our consumers, it may give a wrong impression.

I expected to find some reference to the technique of tariff making, or (and I expected both) fully documented and logical reasons, scientifically based, why certain tariffs had been recommended by the Retail Tariffs Committee and why certain tariffs had been adopted by the Area Boards. Instead, the ordinary reader will gain the impression that all that has happened in standardization, or since 1948, has been the raising of certain price elements in the most popular of the pre-vesting tariffs, to give the increase in the revenue which is necessary and to cause the least disturbance to existing consumers.

We in the supply industry ought to emphasize that tariffs are based on cost analyses. I hope that my voice will have some weight, because it is the voice of years of practical experience of tariff-making with what was one of the largest power-company groups before Vesting Day; and, as Mr. Melling has pointed out, the foundations of the tariffs under discussion were laid before 1948.

The authors have lacked the courage, I think, to state forcibly what they really know to be true, particularly about industrial tariffs.

Take, for example, the annual versus monthly demand charges. The authors look at the bulk-supply tariff and imply that the annual charge is the correct basis, but why do they not say so and stop this clamour from industrialists for monthly charges? What justification is there for a monthly charge? Perhaps it will be said that the industrialist's bills are rendered monthly, and the authors say something about retrospective charges, but this difficulty can be easily overcome by what before vesting date was called a "rising tide" method of charge. My own Board starts the industrialists' year from the end of October. In my view there is no justification for monthly rates, any more than for weekly or daily rates, or—to reduce it to an absurdity—the half-hourly demand that is measured.

I should like the authors' comments on the correctness, in contrast to the expediency, of the present tariffs.

Mr. B. L. Metcalf: The first question I should like to ask is "what is a consumer?" In 1953 the National Coal Board purchased 2 605 000 MWh from various electricity Boards and generated 1 554 000 MWh themselves. This total of 2 605 000 MWh was purchased under a great variety of terms and conditions negotiated at different levels of our organization throughout the country, although by and large the load factor at each point of supply is the same—between 45 and 55%—and the hours of the day at which the demand is made are the same. If we were treated as one consumer, should we not be entitled to better terms?

Our Divisional boundaries differ from those of the Area Boards, and in some Divisions we take a supply from three

ifferent Area Boards; for example, in our South-Western)ivision there is a variation of 30% in the price we pay for lectrical energy at about the same load factor. This disparity 1 charges is illustrated in the C.E.A. Annual Report which gives 1e industrial tariff as 1·317d./kWh in Kent, 1·39d./kWh in omerset and less than 1d./kWh in South Wales and Yorkshire. 'here are no doubt sound reasons for this from the Area Boards' spects, but it means that purchasers are paying widely different rices all over the country for electricity supply required between 1e same hours of the day and at roughly the same load factor.

The difficulties—and dangers from the consumer's point of iew—of a standard tariff make it a doubtful proposition at the resent time. What could be achieved, however, is a standard et of conditions. We find a disparity of view on technical 1atters existing even within one Area Board, between the Sub-rea distribution engineers. For example, one Sub-Area engineer 1sists on busbar protection on the main switchgear, whereas his olleague in the adjacent Sub-Area thinks it unnecessary. In 1e district we were unable to get confirmation in writing of the hort-circuit level on the 11 kV switchgear, yet we could obtain o undertaking that we should be compensated if we had to eplace the colliery switchgear at a later date because of a mis-alculation on the part of the Area Board regarding the short-ircuit value.

There are many other questions which affect the price of lectrical energy and which are omitted from the paper. Who hould pay for the transformers, or for the land required for the ubstation or for the connection to the nearest Area Board line?

There is perhaps some merit in being able to pay the same price or petrol everywhere, averaging out all the distribution charges. 'he authors may reply that there are zonal charges on the prices f coal, too, but we pay these back in the cost of the electricity, wing to the coal clause. The Board's electricity bill is well ver £10 000 000 per annum, and the coal clause ensures that e pay back to the C.E.A. any increases in the cost of delivering 1e coal into the boiler furnaces—and also the cost of handling 1e ash.

Some of our Divisions have negotiated divisional tariffs and thers area tariffs, but there is no standardization of contract con-itions, and this is something I would commend to the authors.

Mr. D. J. Bolton: The reform of tariffs following nationaliza-on could involve two distinct things—unification and improve-1ent. The first stage is to get everybody on the boat, and the econd to steer the boat in the desired direction. The Act itself nly enjoined the first, but the Ridley Committee made sugges-ons about the second, and most people will agree that both are esirable. It is merely a question of timing. One might have oped that the two stages could be carried out simultaneously, 1d that when one tariff took the place of 50 it would be not nly simpler but better than those which it superseded. Whether r not this is wishful thinking, it is obvious that the authors have o such ideas, and are quite satisfied with the first stage.

For example, in Section 3.3 they lay down the two criteria for omestic-tariff acceptability—note the key-word "acceptability" -as being one which secures the desired total revenue and which volves the minimum alteration in total revenue from the con-1mers in each room group. Similarly, from Section 4.4 Mr. Ielling has already quoted the statement regarding industrial ariffs that two things are paramount, safeguarding revenues and miting disturbance. I realize that this is a paper on tariff andardization and not on tariffs, but I should have liked to e the authors adopt a rather more critical approach to the bject and consider whether acceptability is the only criterion r whether something more ambitious could be attempted.

As an example of their non-committal, and one might almost y rather complacent, attitude, the question of the most desirable blocks, in Table 1 and elsewhere, is examined purely from the aspect of minimum revenue disturbance; there is no hint that a different proportion of those room numbers might give a closer approximation to the costs. As a further example, in Section 4.3 they say "One of the major problems was the monetary disturbance to consumers resulting from new tariff levels, and careful consideration was necessary to ensure that equitable treatment was afforded over the full range of demands and load factors." It would appear that by equity they merely mean continuity. Of course, as the late Dr. Joad would have said, "It all depends on what you mean by equity"; but if some consumers were not in the past paying their fair share of the costs, is it equitable to perpetuate the position?

Within this somewhat narrow interpretation, the first stage becomes a grand statistical exercise of finding the highest common factor, or perhaps the lowest common denominator, of consumer disturbance. However, if we accept that particular aim of what may be called "uniformity without tears," or "without brickbats," I think we must agree that the authors in their respective Boards, and the Boards in general, have done a wonderful job in bringing some order out of this tariff chaos. We can only hope that, having got us all on the same boat, they will now go to the second stage and indicate the sort of haven into which they hope to steer it.

In Section 9.2.2 the authors suggest that to reduce the follow-on rate of domestic two-block tariffs will encourage water heating. Unfortunately, as Mr. Rawll points out, one cannot differentiate between water heating and space heating merely by size of con-sumption, and a low follow-on rate would inevitably encourage loads with dangerous peak potentialities. However, the dif-ferentiation could be carried out quite effectively, and without any additional metering or wiring, by the simple expedient of limiting this low tertiary rate to the two summer quarters. In that way the concession could be made at once less dangerous and more generous, and it would encourage not only water heating but any load or type of installation likely to use more electricity in the summer than in the winter.

The authors prefer the off-peak to the time-of-day tariff and suggest that, with the latter, energy may be supplied at a low price between certain hours to apparatus which has already registered a demand on the system at peak hours. I think that there is a misunderstanding here, because obviously the time-of-day method would mean a high rate at peak times and a low rate at off-peak times. If the authors give a consumer an off-peak rate and he then asks for a supply on the same installation at normal times of the day, there must be some price at which it would pay them to supply him, and if quoted this would amount to a time-of-day tariff.

Finally, there is the suggestion of a fixed block for the domestic rate instead of the variable block. Here the authors have quietly insinuated a highly revolutionary proposal which calls for more amplification and support than they have been able to give it.

Mr. G. Rheam: As an industrial consumer I must first con-gratulate the authors on their support of a tariff in which the main chargeable period is confined to the four winter months. This is something for which I have pressed for a long time with only limited success. I am, however, disappointed that the paper does not give the basis on which an industrial tariff should be designed. This is an important matter, and in my opinion the present tariffs are not really satisfactory. A number of them are not fair to all the different types of industrial consumer, and none, I think, discourages avoidable winter peak loads, which is necessary in the interests of ultimate economy.

I am not a tariff expert, but I feel that the normal two-part monthly-demand tariff can never be made to achieve these

objects, and I should like to suggest to the authors a rather different form of tariff. It would be a three-part tariff. First, a service charge, based on active-power capacity required and designed to recover, on the average, the fixed costs on the Board's lines and apparatus required to give the supply. To be logical it should be stepped, because obviously it is cheaper per kilovolt-ampere to provide the apparatus for a large load than for a low load. Secondly, there should be a stepped demand charge, designed to recover on the average the remaining demand-related costs of the Area Board. This should be chargeable only during the morning and afternoon peak hours, Mondays to Fridays inclusive, of the three winter months December, January and February. All other periods of the year should be free of any demand charge. This has great psychological value if you are trying to get an industrialist to reduce his load over the peak hours. For ordinary industry the charge during this three-monthly period should be on a monthly basis, at any rate to start with. The charge should be one-third of the annual rate plus an appropriate percentage, but continuous-process industries should be given a choice of an annual basis. If the omission of November is questioned, I would ask how many times in the last 20 years has the annual maximum demand occurred in that month. Thirdly, there should be a stepped-unit charge, without any element of fixed charge in it and with a proper differential between h.v. and l.v. supplies.

That, in broad outline, is the type of tariff I should like to see. So far as I can see the only disadvantage is that the low-load-factor consumer may be required to pay more; but it is that type of consumer who can most easily improve his method of use of electricity, and in these days of work study, and with the help of the Area Board, I believe that he would in the end pay no more than he does at present.

The advantages are more numerous: (*a*) it is fair to all types of industrial consumer; (*b*) it makes the consumer peak-conscious; (*c*) the chargeable hours are sufficiently small in number to give him a reasonable chance of reducing his load over those hours; (*d*) it will tend to improve load factor; (*e*) the last step in the demand charge will be appreciably less than the demand charge on the bulk tariff, which means that for every kilowatt which can be taken off the annual maximum demand the Board will make an extra profit, which will be an incentive to introduce this type of tariff. I hope that the new Grid tariff will not nullify that incentive, because I look further ahead, to the time when the time-switch will have a temperature control, so that it becomes operative only when the atmospheric temperature is below a predetermined figure.

Mr. K. H. Tuson: Although where tariffs are concerned standardization may be considered an end in itself, the standards should be based on some particular policy. This may be to improve the load factor, to encourage or stifle the increased use of electricity, or to encourage one form of consumption in preference to another. There is no mention of policy in the paper, and I should like to know the guiding principles on which the Boards work.

There is no mention of capital contributions or service charges, except in connection with standby supplies. I am aware of the reasons for such charges, but they are sometimes of considerable magnitude and are always a stumbling-block to the consumer, since they usually operate unfairly between consumers. Cannot the Boards reach an agreed policy on this matter and publish their conclusions?

Why is the maximum-demand charge in some areas much higher for a commercial than for an industrial load? For large consumers a fixed charge based on maximum demand is more equitable than one based on floor area or the number of rooms, and I was interested to read that the authors have no preference for a kilovolt-ampere as opposed to a kilowatt basis for such a charge. I have always thought that the concept of average power factor over a long period was too vague, and it also gives scope to a consumer, if he takes the trouble, to run at a leading power factor during off-peak hours. Presumably there are few places where the Boards are troubled by lack of transformer or cable capacity, and most consumers greatly prefer a kilowatt basis.

Mr. A. E. Marchant: It has been stated that a fundamental of tariff standardization, since vesting date, is that there should be a minimum of disturbance to individual consumers' accounts. With this in mind, Fig. 2 makes an excellent case for the standardization of domestic tariffs on two-part rates based on floor area, particularly as we are agreed that the basis of rateable value is now obviously unsuitable.

From Fig. 8 it is apparent that in 1948 a large proportion of the smaller commercial consumers were supplied on flat rates. This is quite understandable, having regard to the high proportion of very small shops and offices in this class. It is also seen that the application of floor area as a basis of assessment for commercial tariffs has necessitated the subdivision of the consumers in this class into smaller groups, but this has not fully removed the anomalies. Installed load is popular, but is far from being as stable a basis as the "size of premises" is for domestic consumers, and the authors point out in Section 5.5 the difficulty of keeping the assessments up to date. I therefore suggest that for this class a fixed-block tariff, with, say, three blocks, might be advisable. This would be a logical successor to the predominant flat rates of 1948 for the very small consumers. Such a tariff is envisaged in Section 10 as the next step after the initial change over to standard tariffs. It seems that by going directly to the fixed-block tariff for these small commercial consumers the whole of the problems of assessment could be avoided.

I agree with the authors that it is desirable for neighbouring Boards to have the same forms of tariff, but how we shall get standard charges, even with a standard bulk supply tariff, I do not know, for each Area Board must be solvent, in spite of the wide variation in the load characteristics of the individual consumer classes, as shown in Fig. 1, and the different proportions of these classes in the areas supplied by the various Boards.

Mr. G. Davidson (*communicated*): I feel that greater attention should be given to encouraging the off-peak load, in view of future developments in the utilization of electricity. With the developing national solid-fuel situation, restrictions will undoubtedly fall on the domestic consumer of fuel within the next few years, because of increasing prices and shortages. The future for both solid and liquid fuel in the domestic sphere is gloomy, whereas atomic-power developments make the outlook for electricity distinctly rosier. This source of heat energy will be developed rapidly, and within the next decade electrical heating is very likely to form the bulk of the demand. The need to improve the daily load curve is just as evident now as ever before, and unless something is done now to encourage off-peak methods, enormous peak demands will develop without improvement in load factor; it will not be easy to change existing and future installations that are not designed to take off-peak supplies. It will be just as difficult then as it is now to improve the daily load curve.

Before vesting date, electricity authorities with initiative introduced very low off-peak rates, down to a relatively small fraction of a penny per kilowatt-hour, to encourage off-peak loads; but under nationalization there appears to be less imagination than before in this respect, and the off-peak tariff in the London area is barely less than the domestic all-in tariff rate, simply because—as the authors rightly state—there is insufficient economic justification, although in Section 9.1.2 they say that

ff-peak thermal storage heating warrants a low charge per ilowatt-hour. There is therefore very little encouragement for he off-peak domestic heating load. Surely the Area Boards hould be advised to work on principles other than present conomics when necessary to ensure future efficiency?

If we look far enough into the future we may discern the ltimate possibility of a water type of tariff, with fixed charges nly and energy free of charge. Costly high-efficiency generating lant now suggests this possibility and the atomic power stations f the future may bring it about, but it will be a long time, of ourse, before we can introduce such ideas into our tariff tructures.

Mr. J. F. Smith (*communicated*): In Section 3 it is stated that, s a group, domestic consumers spread their use of the supply rom early morning until late at night and help to fill up some f the valleys in the daily load curve. The accuracy of this tatement is not challenged, but it must be remembered that the hape of the daily load curve is itself the outcome of supplying simultaneously various classes of consumer, including domestic consumers. Would it not be more true to say that with wider applications of electricity supply in the domestic, commercial and industrial fields the tendencies of these classes of load to produce peaks and valleys will be lessened?

Fig. 10 does not show the diversity the authors claim, and at mid-day each of the four examples may well be occurring simultaneously.

It is suggested in Section 9.1.2 that energy supplied during off-peak periods should have a two-part nature, so as to maintain equity between degrees of usage. The demand component (or first block in the case of a block tariff) can obviously be much smaller than its peak counterpart, but it is necessary because a flat-rate charge cannot differentiate between off-peak usage, which can vary widely in magnitude and character.

[The authors' reply to the above discussion will be found on page 556.]

NORTH-WESTERN UTILIZATION GROUP, AT MANCHESTER, 15TH MARCH, 1955

Mr. S. R. Mellonie: The paper does not give due consideration o the importance of diversity factor. It is true to say that the upply industry lives by diversity factor, which receives inadequate ttention. As an example, I quote my own case as a domestic onsumer. By making a careful check of the maximum demand, estimate that, if the advertised C.E.A. tariff was adopted as he basis of the charges, I should pay 30% more than under the resent domestic tariff.

The authors rightly draw attention to the importance of ttracting off-peak loads, but a note of caution must be sounded, n as much as the larger off-peak loads may be so described as egards the generating station, but they are certainly on-peak as egards large sections of the distribution system, although they nay occur at midnight. When it is appreciated that the low-oltage network alone accounts for 38% of the total annual harges it will be realized that the m.d. charge for such loads must e appreciable.

Mr. G. V. Sadler: I appreciate the magnitude of the task ndertaken by the Area Boards to standardize tariffs over the ountry, but I hope that the authors' remarks in Section 10, oncerning the constant review of existing tariffs will be borne ut in practice. With industrial tariffs there is room for further ealistic treatment and simplification in the method of charging.

The standard national tariff is rather narrow on the question of ower factor. Those consumers who some years ago installed a air proportion of electric space-heating equipment, and were able o maintain a high power factor on which they received a bonus, re apt to feel disappointed that their efforts are no longer ecognized. I would even suggest that consideration be given o a long-term space-heating tariff based on a 5- or 6-year period. t is not possible to establish a realistic space-heating tariff based n any one winter, and if more account were taken of the cyclic ariations of severe cold periods, it would tend to encourage the se of electric space-heating equipment.

Mr. T. E. Daniel: Tariffs have always been the playthings of nanagers of electricity undertakings, and frequently they were ased upon theoretical considerations, which made them very omplicated. A tariff is a means of collecting income from arious consumers, and provided that it is generally fair as etween one class of consumer and another it does not really natter whether each consumer pays the exact cost of affording he supply or not. There is no reason why there should not be uniform tariff throughout the country, provided that the nonetary content could be varied as between one area and nother, depending upon the efficiency of working.

The paper suffers perhaps because of the absence of any indication as to the actual monetary content of tariffs, and it is not easy to see whether the authors favour a high standing charge and a low running charge, or vice versa.

At the end of Section 4.3 the authors mention "a tariff which would bear little relation to costs," and I wonder whether the actual cost of affording any particular supply is known.

In Section 4.5 a ceiling price is suggested, but the object of a two-part tariff is surely to encourage the use of electricity over as long a period as possible, and any attempt to take the consumer away from this idea frustrates the object of the tariff. A two-part industrial tariff is formed to encourage the consumer to keep down the maximum demand while making full use of the energy. Do the authors consider that all tariffs should be related to the bulk-supply tariff?

Mr. A. Stewart: I feel it desirable that variable-block tariffs for commercial and industrial supplies should be restricted to supplies of about 50 kW and over. Apart from being expensive in administration and manpower, it is also bad for consumer relations if frequent visits by assessors or inspectors are always followed by increased charges—even if these are of a minor character.

In Section 4.2 the authors give details of the recommended industrial tariff, and I should like their opinion on the recommendation that a maximum-demand charge tariff should be offered to a consumer with a demand as small as 5 kVA. Having regard to the high cost of metering and the high administration costs associated with monthly accounts for this class of consumer, I feel that the minimum should be raised to at least 50 kVA.

In Section 4.3 the authors refer to the procedure for fixing the standard charges and to the major problem of monetary disturbance to consumers. This same factor is also referred to in the Sections dealing with commercial supplies. From Table 2 it is seen that increases of 16·28% were required, but when we remember that the cost of electricity to industry as a whole represents only a very small percentage of the total cost of production, even a 16% increase may mean something less than 1% when related to the total costs.

Mr. W. E. Swale: The degree of rationalization of electricity tariffs, which has been achieved in a relatively short time (with the promise of more to come in the near future) when compared with the chaotic state of tariffs before Vesting Day, is surely one good argument in favour of nationalization of the industry.

Could the authors elaborate their comments on ceiling prices (Section 4.5). Do they mean that every maximum-demand tariff

should carry with it a ceiling price or merely that, usually, every maximum-demand tariff should have a fixed-block tariff as an alternative?

Sections 4.7 and 9 illustrate the careful thought which Area Boards are giving to the possibilities of exploiting every possible application of such "abnormal" loads. It is not easy to interpret all the many opportunities which are offered, and consumers will be well advised to consult their local Area Board officials, especially when intended new applications tend to alter normal conditions of supply.

It is useful to have a measure of the very rapid development of the uses of electricity in the last 30 years, which the following figures indicate:

	Year to 31*st December,* 1924. *Basis of Weir Report*	*Year to* 31*st March,* 1954. *B.E.A. Report*
Consumption per head of population in United Kingdom	110 kWh	1 100 kWh
Average cost per kilowatt-hour	2·047d.	1·373d.

[The authors' reply to the above discussion will be found on page 556.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 28TH MARCH, 1955

Mr. W. A. Carne: It will be noted that after a lapse of nearly 7 years the standardization of tariffs is still far from complete in some Boards' areas. Nevertheless, by following the logical sequence of first collecting information, secondly designing the tariffs, and thirdly applying the tariffs, standard domestic, farming and commercial tariffs for this area were published in June, 1951, and they were applied with a negligible number of complaints from consumers.

However, some of the standard tariffs in this area are not entirely in accordance with Retail Tariffs Committee recommendations, and are therefore regarded by the C.E.A. as interim tariffs. The departures we have made from the recommendations are due to the fact that the information collected with regard to consumers in this area cannot be reconciled with the recommendations made by the Retail Tariffs Committee, who made their decisions before they had a chance to collect and study similar information.

In Section 3.3 the authors describe the procedure for fixing the standard domestic tariff; the sequence as they give it is:

(*a*) Discussion with the Consultative Council.
(*b*) Decisions as to tariff structure.
(*c*) Collection of information on which the tariff could be calculated.

I suggest that the first step—and not the last—is the collection of information, and that the information must not be collected with any preconceived ideas as to the form of tariff that is to be adopted.

Secondly, the tariff should be fixed, i.e. calculated with due regard both to costs and to effect on consumers, and thirdly the tariff should be placed before the Consultative Council with the necessary supporting data.

I would mention here that the Electricity Act, 1947, which created the Boards and the Consultative Councils, requires Area Boards to notify the Consultative Councils of their general plans and arrangements, and I suggest that it is far better to put carefully considered plans in their final form to the Consultative Council than to discuss proposals and be later faced with putting into effect suggestions that have been made without the necessary detailed information and knowledge.

I note also in this Section that a sample of consumers was selected, it is said by statistical methods, and that the final sample consisted of 210 000 consumers, i.e. 18%.

Using modern statistical methods I should have said that, after allowing for the fact that information was probably required for some relatively small groups of consumers, an overall sample of 3% would have been more than adequate; for large groups of consumers a 1% sample gives quite accurate results. A small sample is more manageable and can be sorted and tabulated in several different ways to provide information that could not readily be obtained from a large sample.

For industrial tariffs (Section 4.2) we do not agree in this area with a tariff based on floor area. Such a tariff may seem attractive to those who think superficially only in terms of the lighter industries; in this area we have not lost sight of the fact that the consumer buys energy, i.e. kilowatt-hours, and although partly educated into paying for demand which is of no use to him, he definitely views with suspicion a charge based on his floor area.

With reference to experience in introducing standard industrial tariffs (Section 4.5), this area is not recognized as having standard industrial tariffs because such tariffs have not been published. The practice adopted has been to incorporate the Board's standard industrial tariffs in agreements which specify the ownership of the service equipment, the maintenance of the equipment, metering, access to premises and use of equipment by the Board for other purposes.

The appropriate standard industrial tariff, of which the consumer has the choice of three, is inserted in the agreement together with an appropriate variation in respect of high-voltage or low-voltage metering, fuel-cost adjustment and power-factor rebate or penalty where appropriate to the particular type of supply.

With reference to commercial tariffs (Section 5.3), it is observed from the Table showing the monetary disturbances that for a change in tariff bringing in, on an average, say, 5% increase in revenue from consumers, 12% of the total consumers, i.e. one shop, office or other premises in every eight along the street will be faced with a bill showing anything from a 50% to over 100% increase in cost. This, surely, is a state of affairs which would cause a minor riot and throws grave suspicions on the recommendations of the Retail Tariffs Committee upon whose structure the commercial tariffs have been based.

Although the North Eastern Board has published a farm tariff, we are not altogether satisfied that it is possible to draw a line between a farm as generally understood and an industry based on rural products. The farm tariff covers the majority of farms where the domestic usage can be a large part of the total, and to encourage domestic use the final rate of the farm tariff is the same as the final rate of the domestic tariff. However, this rate is uneconomic when applied to some large users on the borderline between farming and industry, i.e. grass and grain drying on a large scale; a further difficulty arises in the supply to a chicken hatchery which will require a 500 kVA transformer and produce chickens on a conveyor-belt system by the million; a factory of this nature has a very heavy seasonal load covering only the winter months.

Mr. E. C. Lennox: The paper gives the impression that in the application of the new tariffs consideration has been given to avoiding any considerable increase to any type of consumer rather than the strict application of a tariff bearing on the costs involved in providing supplies. Nevertheless it was right to avoid a considerable consumer upset and no doubt time will enable further variations, where necessary, to bring the tariffs further into line with the costs of supply.

In due course the domestic two-part tariff could be dropped, leaving available the variable-block tariff for general application. I favour the adoption of "assessable rooms" as the basis for variable blocks or standing charge—a method used in this area for many years. The difficulties of its application are well known. The definition set out in Section 3.5.1 (sculleries and kitchenettes) has now been accepted, but a lot of discontent could have been avoided if so-called kitchens of less than 50 ft^2 had been discounted.

It is vital that, although the national recommendation of tariff structure may be similar, it is not extended to include charges per kilowatt-hour or for demand. These must vary in different areas, and so long as Gas Boards have tariffs varying so greatly in their different areas, then so long is it undesirable to consider standardization of rates. We must also remember that Gas Boards are saved the uneconomical costs of providing supplies in rural areas.

One of the difficulties of the commercial tariff is that consumers with large floor areas, especially in urban and rural areas, will have to buy more energy at the high rates before obtaining the lesser rate available for heating, etc. It is necessary that alternative methods of charge are made available.

No mention is made of the use of relay systems for remote control from power stations by impulses over the mains; this could allow the use of thermal-storage apparatus at many times during the year other than the hours stated in Section 9.1. The control of such apparatus from central points would depend on known conditions, and would vary in different parts of the country and at different times of the year.

Finally, I cannot foresee, as do the authors, the application of fixed-block tariffs for domestic, farm and commercial consumers. I would prefer the retention of the variable-block tariffs, which relate somewhat to the size of premises and their electrical loads.

Mr. G. P. Cundall: In Section 9 the authors favour restricted-hour tariffs which cover the use of electricity at off-peak times only. They do not, however, favour a two-rate or time-of-day tariff, because it allows cheap electricity to be consumed at night by plant which has contributed to the peak demand during the day. This is difficult to understand. Surely it is very useful to have a factory working a night shift, even with the plant that contributes to the maximum demand? One would have expected any use of electricity at these times to be encouraged to some extent, even accepting that the best terms should be available in the restricted-hour tariff.

Good load factors are also encouraged by maximum-demand tariffs. Since the size of all the electrical equipment needed to generate and distribute energy is governed by its apparent power loading rather than by active power loading, the reasons for the authors' statement, in Section 4.6, that there is little to choose between the measurement of the two demands are not apparent. At the outset the authors say they do not intend to discuss this matter in detail and so necessarily leave unanswered questions in the consumer's mind. Some of the fairly recently published Area Board tariffs incorporate a kilovoltampere m.d. charge, and consumers are therefore encouraged to improve their m.d. power factors to 0·97 or more. Other Boards measure kilowatts and average power-factor, and levy a penalty if it should be less than a prescribed value—usually 0·8 or 0·9. In other areas consumers are required in their agreements to maintain a certain power factor, but no steps are taken to see that they do. To the consumer who operates factories in different parts of the country, such a situation is confusing; if he understood the subject, the one in the kilowatt-demand area with a good power factor would think it unfair that his m.d. charge should be the me as his neighbour's whose power factor is only 0·5. That there is not, in fact, much difference really between these tariffs may be true, but there certainly appears to be some. To the engineer it suggests that there is evidently no certain knowledge of the costs of supplying reactive energy. No doubt this cost is small compared with the main ones faced by the industry, but I would have thought it sufficient to justify more than the passing reference which the paper gives it.

Mr. W. H. Burton: The fairest tariff, and the one most easy to defend on logical and economic grounds, is a two-part tariff with a demand charge related to the measured maximum demand created by the consumer, plus a running charge per kilowatt-hour. If the demand charge can be in two parts—one component related to the capital cost incurred in providing the supply, e.g. a service charge, and one component related to the consumer's maximum demand at the time of the system maximum—so much the better. However, it is not practicable to apply such a tariff to a large number of consumers because of the metering problems incurred, and resort has to be made to block tariffs.

The variable-block tariff based on floor area, connected load, number of rooms, etc., is fairer than the fixed-block tariff, but such tariffs are usually complicated and not understood by the general public. The 1947 Act requires Electricity Boards to simplify their tariffs, and some of the variable-block tariffs are far from simple and the cause of much dissatisfaction to consumers. There is on this score much to be said for a fixed-block tariff, and I agree with the authors that for smaller consumers it is likely to be the type adopted in the future.

How would the authors deal with certain classes of consumers who have a very poor load factor, but whose usage of the supply is often of an off-peak nature? I have in mind fish-frying loads or licensed premises with a large concert room used only at weekends and similar premises. Somewhat similar is the case of a small office block with electrical heating forming part of a large warehouse block charged on a floor-area basis, the total consumption related to the total floor area being such that the whole of the supply would be charged at the primary rate of 4d./kWh or more. Do they agree with the method adopted in some areas of splitting the installation, metering each portion separately and charging each on its own merits?

Mr. R. R. Pattinson: The standardization of tariffs clearly has much to commend it, but should not be taken too far. Perhaps when the present phase of concentration to a minimum number of tariffs has been completed, it may well be found desirable to fan out again to cover special types of load.

To fill in the valleys of the daily load curve is obviously of paramount importance, but since consumers may not welcome using off-peak energy, the tariffs should be made as attractive as possible. The authors have recognized this by suggesting a lower maximum-demand charge for off-peak times, but it seems that there is an argument against levying any charge at all on this account. Is it not true that the plant and system costs have already been recovered by the m.d. charge for the on-peak demands? If so, off-peak energy should carry no demand charge, and this in itself would strongly appeal to prospective consumers.

Experience in the United States and investigation in Britain support the view that a measure of power-factor improvement can result in more effective system loading, and the installation of capacitors appears to be gaining favour. Power-factor improvement at the load has much to commend it, but this will almost certainly involve expenditure by the consumer. Since the consumer will spend no capital unless he is offered adequate compensation, why not offer a tariff making attractive power-factor improvement to a degree advantageous to the Area Boards?

It is well known that induction motors feed power into a fault and that this power can be appreciable when large motors are

involved. If this factor were considered in the planning of the supply to a prospective consumer, it might be found necessary to increase the short-circuit rating, and so the cost, of the controlling circuit-breakers. How do Area Boards deal with a problem of this nature, and is the consumer required to contribute to the additional expenditure?

The authors' remarks on domestic off-peak loading are disappointing. With 300000 new houses a year being built, the potential energy consumption is not one lightly to be disregarded. I therefore suggest that if the C.E.A. or Area Boards were to work in closer co-operation with local authorities responsible, the design of the houses might be adjusted to make possible floor or panel heating as an off-peak load. Ripple control over the mains would obviate the cost and maintenance of time switches, and the meters might be designed to incorporate an element susceptible to mains control, thereby avoiding the need for two sets of meters.

Mr. D. Rudd: The effect of nationalization has been to prevent the supply industry from formulating its commercial policy in the old manner, by trial and error, but at the same time an opportunity is given to achieve a formal solution to the problem and Section 37, Sub-Section (3) of the Electricity Act states how the problem is to be approached.

> The tariffs (fixed from time to time by the Area Boards) shall be so framed as to show the methods by which and the principles on which the charges are to be made as well as the prices which are to be charged, and shall be published in such manner as in the opinion of the Area Board will secure adequate publicity for them.

There is an equivalent clause for the Central Authority.

The operative word is "principles," and in effect the Boards and the Authority are instructed to substitute principles for opinions—however responsible and sound those opinions may be—in the formulation of their commercial policy. So far as I can ascertain, no such principles have been published.

I believe that, with official co-operation, a system of analysis deriving from generally acceptable principles could now be made available. It would enable the Area Boards and the Authority to obtain complete and satisfactory information regarding the proportions in which the costs they incur are properly attributable to specific loads. Would the authors be interested in such a system of analyses?

Mr. E. H. Sadler: Area Boards should approach uniformity with caution, and whenever possible, when formulating their domestic tariffs, take full advantage of the a, b and c variations proposed by the Retail Tariffs Committee and set out in Section 3.2, i.e. they should offer at least two forms of domestic tariff, such as two-part or block tariffs, although each form will, on the average, give the same revenue. If only 10% of a Board's consumers are allowed their preference towards one form or other of these tariffs, it has, at no cost to the Board, removed from thousands of consumers a potential or actual sense of grievance.

In Section 9 we have two types of off-peak load, the small supply such as battery charging fed from an l.v. network and supplied on a published tariff, and we have the bulk thermal-storage installations for large commercial buildings or blocks of flats. The latter should be the subject of a special agreement for each supply and the tariff for large off-peak supplies should not be a published one.

For a large thermal-storage installation the hours proposed by the authors are applicable to a supply afforded from h.v. feeders to a substation on the consumer's premises. However, if this same supply were made at low voltage from a city network, the mid-day boost period would have to be restricted, since the mid-day drop in load on a city network is of 1–1½ hours' duration. The city load is well down by 5.30 p.m. so that the 6 p.m. switch-on is clear of the l.v. network peak. Another possible condition is a large block of commercial premises or a community centre or block of flats with floor heating, located in the centre of a housing estate. If a bulk off-peak supply is given to these premises from the l.v. network, a 3-hour mid-day boost might be no difficulty, but to avoid the evening peak on the l.v. network the switch-on period would have to be restricted to 10.30 p.m. because of the maximum load period on the domestic network. It appears essential for the Boards to reserve some latitude for times of off-peak supplies and also to adjust the rates for the extra losses incurred in providing a supply from a network.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. A. O. Johnson and **N. F. Marsh** (*in reply*): A number of speakers have criticized our views with regard to the avoidance of monetary disturbance to consumers, but we still maintain that the Area Boards were justified in avoiding the extreme disturbance which would have been caused if an attempt had been made to adhere too closely to theoretical tariff structures during the early stages. The Retail Tariffs Committee recommended a basic structure for tariffs but not, of course, the monetary contents, and if this question of monetary disturbance had not been carefully watched some consumers' accounts would have been increased by 300% or more in the initial change-over. The first stage of tariff standardization—which has involved so many major changes and bold decisions on the part of Area Boards—is largely completed, and the second stage which is now commencing will no doubt remove a number of anomalies between the tariffs of the Area Boards and narrow the gap between theory and practice.

Mr. Rawll really answered his own question, as it is surely a great advantage to have decreased the number of tariff-making bodies from 541 former undertakings to the 14 Area Boards. Miss Lockhart's suggestion for a national basic domestic tariff with surcharges and discounts in the various areas would be difficult to operate and would cause a good deal of discontent amongst consumers who might not understand the reasons for the different charges. Mr. Carne's views on a smaller domestic sample would no doubt be appropriate for future surveys, now that there is some uniformity in domestic tariffs, but when dealing with initial standardization from a large number of former tariffs it was considered advisable to play safe and use a larger sample; the accurate results of some of these surveys have, we think, justified this decision.

Mr. Jervis and other speakers considered it unreasonable to group such divergent types of premises as large stores and churches under the heading of "commercial" premises. The so-called "commercial" tariffs, however, have to provide for the residue of premises left over after fixing tariffs for domestic, farm and industrial premises: this does not preclude appropriate variation in the basis of assessment to suit the load characteristics of the different classes of premises catered for by this tariff. There was also some criticism of the bases of assessment for commercial tariffs. We agree that the floor-area basis is not suitable for large stores, but most Area Boards have a demand-related tariff which should be suitable for such consumers, leaving floor-area tariffs for the smaller premises.

Mr. Tuson queried the higher demand charge made for commercial premises as compared with industrial; this is because the commercial load is mainly a lighting one, generally of low load factor, with the highest demands in the peak periods. In reply

to Mr. Stewart, we see no useful purpose in reversing the recommendations of the Retail Tariffs Committee by making variable-block tariffs available only to supplies of 50 kW and over. Block tariffs are most suitable for small consumers and should be available for loads of up to 50 kW. With regard to the relatively high cost of measuring the demand of supplies as small as 5 kVA, this is not so serious as it appears, as thermal-type demand indicators or small combined kilowatt-hour and maximum-demand meters can be used. The number of such small consumers who would choose the demand-type tariff is not very great. Mr. Rawll asked why such a small number of commercial consumers took supply on two-part tariffs: these are mainly the larger consumers who are small in number compared with the remainder. There is little to choose between the kilovolt-ampere and kilowatt bases for tariffs so long as the latter has an appropriate power-factor clause; each form of tariff encourages power-factor improvement. In the standardizing of industrial tariffs previous practice in this matter had to be taken into account, for it would have been wasteful to change over large numbers of kilovolt-ampere metering equipments to kilowatt equipments, or vice versa. This is a justifiable case for continuing past practice.

Three speakers complained of the lack of special terms and long-term agreements. We understand, however, that in most Areas consumers with special or abnormal load characteristics can obtain terms appropriate to their particular cases under agreement for periods of up to 5 years at least, and possibly up to 10 years, subject to a clause permitting review of the terms in altered circumstances; it must be appreciated that no business undertaking can contract for years ahead at fixed prices.

The three-part type of tariff suggested by Mr. Rheam is not new, but it involves difficulties in fixing the service charge; negotiations to determine the service capacity a consumer requires are always difficult when the consumer is asked to pay a direct levy on service capacity. Mr. McLean is entitled to his views on monthly tariffs, but as the majority of industrial consumers, through their organizations, stated a preference for such a tariff, it was provided. Alternative annual tariffs can also be made available so as to cater for all tastes. Mr. Metcalf draws attention to the difference between the average prices for comparable supplies afforded by different Area Boards, but these will normally be found related very largely to the basic fuel costs.

Mr. Bolton's proposal of a tertiary rate in the domestic tariff for the two summer quarters only is theoretically sound, but with continuous meter-reading it is difficult to operate. There were also a number of comments on the opinions we expressed with regard to future fixed-block tariffs in lieu of variable-block tariffs. We can only say that, if the full context of the paragraph is studied, there is much to be said for it.

Our main objection to time-of-day tariffs is that they are not effective in diverting load from peak periods to off-peak periods; in practice, the size of price differential required to do this would render the tariff quite unacceptable to consumers. In our view it is better to offer special low terms only for those loads which can be kept off the peak altogether by a time switch, and there is only a limited number of applications which come within this category. The impulse control of off-peak load, mentioned by Mr. Lennox, cannot be considered for general application; such control systems are limited in practice to localities where their advantages are not outweighed by their capital and operating charges.

Mr. Davidson forecast a tariff consisting of a fixed charge only with all energy free, but this would encourage wasteful use.

DISCUSSION ON "ELECTRIC LIFTS IN POST-WAR HOUSING"*

BEFORE THE NORTH-WESTERN UTILIZATION GROUP, AT MANCHESTER, 16TH FEBRUARY, AND THE NORTH MIDLAND UTILIZATION GROUP, AT LEEDS, 23RD NOVEMBER, 1954

Mr. T. Pratt (*at Manchester*): In view of the extensive precautions being taken to protect lifts on housing estates from misuse, has there been any reduction in the number of incidents, indicating that in the course of time at least some of the precautions may be dispensed with?

Mr. J. N. Welch (*at Manchester*): I note that the author favours normally-closed-door operation on the grounds that it discourages children from playing in the lift. My experience is that children will play with a lift irrespective of the type of operation, and normally-closed doors can allow a small child to be imprisoned in the lift without being able to re-open the door, since it is unable to reach the pushbuttons, which have been positioned out of its reach. With normally-closed doors the control circuit is more complicated, for the landing pushbutton both performs the function of summoning a lift and acts as an "open door" switch. Furthermore, it is necessary to fit an "open door" pushbutton in the car, thus further complicating the control and providing another item which could be abused by being wedged.

Of the two types of door safety-edge mentioned by the author, although the flexible type gives greater protection, owing to its sensitivity up to nearly 180°, it is inherently weak in that it could be easily damaged, and a small boy with a penknife is within easy reach of 100 volts. The totally-enclosed type is more robust but does not give the same protection, particularly to small fingers round slam posts or architraves. In order to provide the greatest protection it has been necessary for the lifts under discussion to have a comparatively expensive safety edge fitted on every landing door. I am sure that there is great scope for improvement in safety or sensitive edges, and the need exists for an inexpensive protective device to give full protection for both car and landing doors without the need for duplication at each entrance.

It would seem from the paper that the main reason for removing the stop pushbutton in the car was because it was possible to stop the lift in a critical position and thus jam the door operator. This appears to be tackling the problem from the wrong end, and a better solution would have been to modify the door gear to eliminate the possibility of jamming. If the landing lock circuit becomes broken while the lift is travelling, the lift will naturally stop, but, in addition, the car door will open. Is the author satisfied that these conditions are safe, bearing in mind the permissible 5 in gap between the car sill and the wall of the lift shaft?

On this specialized type of lift it seems that, for every refinement added, two or three protective devices have also to be fitted to guard against malicious abuse. Are too many refinements that are not really necessary being added, thus complicating the equipment and increasing the number of potential stoppages? Would it not be better to fit simple straightforward lifts with manual shutter gates on car and landings, similar to

* MORLEY, C. G. L.: Paper No. 1556 U, November, 1953 (101, Part II, p. 69).

those installed before the war for Leeds Corporation? There is no doubt that the simplification of the equipment reduces the number of stoppages. As a comparison, if we take the author's figures, after all the modifications have been carried out, the average breakdown rate is one in every 12 000 lift journeys, whereas according to figures given by the Central Housing Advisory Committee of the Ministry of Health for the 88 lifts installed for Leeds Corporation, the average breakdown is one in every 20 000 lift journeys.

Mr. G. V. Sadler (*at Manchester*): Once a journey has been initiated by pressing the car button, must it be completed and landing doors opened before another journey can be commenced, or can children, intent merely on having a ride, manipulate the buttons and cause the lifts to ascend and descend continuously without the landing gates being opened at the end of the travel?

What provision is made for ultimate limit switches at the top and bottom of the lift travel, and is there any provision for opening the main motor circuit, or only control circuits, by these switches?

Mr. A. D. Ryder (*at Manchester*): When a particular form of abuse is prevented by an addition to the equipment, e.g. the fairly elaborate time-controlled cut-off scheme to prevent continual operation or continual reversing of the power-operated doors, we should be wary of applying such additions to other types of lift; and even for this type our efforts will be best directed to providing the protective effect undoubtedly required by the simplest possible means. It is a well-established principle that the more relays, contactors and interlocks, etc., there are in a control gear, no matter how reliable each one may be, the more sources of breakdown there are; and, depending on the standard of maintenance, elaboration can easily be carried too far.

Has the author any evidence of the relative proportions of stoppages due to passenger interference and to breakdown of equipment on lifts of the simplest type, compared with lifts on which all the modifications have been made?

The author mentions the reduction in weight of the car, and consequently of the balance weight, obtained by using aluminium alloy in the construction, although this effect is no doubt partially offset by the weight of the door-operating gear. What is the proportion of the out-of-balance loading to the total weight hung on the winding sheave, which has, of course, a direct bearing on the avoidance of slip in the rope grooves?

With regard to the suspension of the pulleys for the safety-gear operating rope from the underside of the gear-room floor, the reason for the more usual practice of taking the rope up through the floor is to carry it over the gear joists, so that one can be sure that it will be supported independently of the pulleys in the last resort. One must to a certain extent pay for the advantage of putting the pulleys under the floor by arranging for them to be of ample strength and to be tied into the floor steelwork, so that breakage of the safety rope is still the limiting factor.

Mr. W. A. Gibbon (*at Manchester*): The paper mentions that where passenger lifts are installed a subsidy is payable up to a maximum of 50 flats per lift. Does the author consider this ratio appropriate?

Architects are invariably advised by lift engineers to use the overhead drive system, because of its greater efficiency and its lower cost; and although I naturally sympathize with the wish to retain clean lines in building design, I feel strongly that architectural niceties must be related to circumstances. Where an overhead motor-room is clearly indicated, it must be accepted and integrated in the building design; whereas this may be difficult if consideration is not given at an early stage, the motor-room can undoubtedly be designed to form an attractive architectural feature if considered at the outset.

Mr. F. H. Johnson also contributed to the discussion in Manchester.

Mr. B. Pirie (*at Leeds*): With pushbutton operation dealing with only one call at a time, is a speed of 100 ft/min sufficient for a travel of eight or more floors, or is the waiting time sufficient to cause impatience? What is the maximum number of flats which can effectively be served by one lift at this speed?

Does the author believe in vision panels in otherwise solid doors?

Are obstructions deliberately placed across the bottom tracks of the doors, so that the sensitive edge or retractable shoe is impeded and the doors re-opened automatically? This could continue until the door motor burned out.

Mr. J. N. Welch (*at Leeds*): Has trouble arisen from brick-dust and grit in oil- or grease-lubricated guides, and have experiments been conducted with guide shoes which do not require lubrication?

Lifts with solid doors introduce ventilation problems, particularly when a laden car is stopped between floors, and I should like the author's views on what constitutes adequate ventilation.

Are stop pushbuttons fitted in the directional collective-control lifts that the housing authorities are now installing?

Mr. J. Stork (*at Leeds*): Will the author give details of the rope life obtained with the lifts described, and indicate the type, construction and tensile strength of the ropes favoured by the housing authorities?

The paper states that the escape hatch should be used only when it is impossible to drive or hand-wind the car to a landing level. Has such a circumstance arisen?

I was surprised to learn that housing authorities favour trap-doors for access to the motor room; if the maintenance engineer received an electric shock and fell on to the trap-door, it would be difficult to rescue him.

Are the cars for silent-operation lifts isolated from the steel slings?

Mr. A. J. Coveney (*at Leeds*): The decision to standardize on roof-top motor-control chambers appears to offer disadvantages in two respects. These exposed concrete structures will be subjected to low temperatures at night, and this is borne out by the need for silicone fluids in the dashpots; some form of heating and ventilation is necessary, particularly to prevent condensation and troubles resulting from moisture on insulation. The other disadvantage would appear to be their access during winter and the danger—unless safety precautions are taken—for the maintenance engineers trying to reach these motor rooms during severe weather conditions.

Messrs. J. Leiper, J. P. Feather and **K. I. Mason** also contributed to the discussion at Leeds.

Mr. C. G. L. Morley (*in reply*): In reply to Mr. Pratt, the time that these lifts have been in service is, I think, too short to expect to see any change in general sociological trends, but ultimately I am sure that misuse will die away.

Mr. Welch refers to only one reason why parking with closed doors is used, and the other reasons, i.e. avoiding the ingress of dirt and rain into the lift car and well, may have been overlooked by him. I have no record of children being trapped in the lif car and do not expect to have this condition, since the "open door" pushbutton is the lowest on the car control station.

I have not yet tested a sensitive-edge device that has proved any more satisfactory than those at present in use.

Mr. Welch has entirely misunderstood the paper if he suggests that the removal of the stop button was merely to avoid jamming the door gear. It was but one step in the chain of circumstances whereby the passenger is prevented from stopping the car in travel and gaining access to the interior of the lift well. He has overlooked the locking of the car door and the securing of the escape hatch. The hazard for the passenger of the 5 in gap

etween car sill and lift well therefore does not arise on these ifts.

The comparison with the lifts installed for the Leeds Cor-oration at Quarry Hill is really not valid, since these lifts are f 2-person capacity only and therefore do not provide the acility for carrying perambulators, items of furniture and the eavy loads that the 8-person lift does. Indeed, my experience s that 2-person lifts are relatively little used because their menity value is so low.

The ultimate limit switches mentioned by Mr. Sadler are in he control circuit so that the main breaking contacts used are onstantly being proved serviceable by their operation in the ormal functioning of the lift.

Mr. Ryder will be aware of the noise factor in lift installations ising manually operated gates and the inconvenience experienced lue to passengers not properly closing these gates. These are ome of the reasons why automatic door operators are used on he lifts dealt with in this paper. No comparable figures for the reakdown rate of lifts with manually operated doors can herefore be given, but with passenger-operated lifts having nanually operated gates in office blocks the most frequent ause of unserviceability is that the lift gate is left open.

The tractive effort transmitted between the sheave and the ope depends, amongst other factors, on the choice of the rope nd the sheave groove used and the percentage out-of-balance. This out-of-balance varies between manufacturers, and is thus nly one factor bearing on rope slip.

The strength of the fixings and general arrangement of the afety-gear pulleys when fixed under the floor of the motor room loes take into account the breaking load of the safety gear rope.

I agree with Mr. Gibbon that motor rooms can be formed nto an architectural feature, and the clock on Shell Mex House n London is an extremely good example of such treatment.

Mr. Pirie will appreciate that amenities must be related to cost, nd eight storeys are considered to be the limit for non-collective ontrol, after which fully collective control is fitted. The number f flats which can effectively be served by one lift is again a uestion of balancing amenity against cost, but architectural onsiderations are obviously involved. Up to eight storeys, an verage of some 35 flats are served per lift

If doors are continually prevented from closing, a protective system is incorporated in the control system that will open the door-motor circuit. The control circuit is automatically reset whenever a call is imposed on the circuit.

The shafts of these lifts are generally so situated that they are subject to wide variations in seasonal temperature and humidity. Rust would be expected to form on any surface unprotected by paint or oil, and as this would seriously affect the life of the unlubricated shoe—as distinct from a guide roller—such shoes have not been used.

Adequate ventilation of a stationary car containing passengers for a period with doors closed is undoubtedly obtainable only by means of a fan, but this provision is, I think, an unnecessary expense. Ventilation slots at the top and bottom of the sides of the car have proved quite satisfactory. Stop buttons are not now fitted in any of these lifts, whatever the type of control, provided the lifts are fitted with solid doors on both car and landing.

In answer to the point raised by Mr. Stork, it is my experience that 6/19 ropes of 12–6–1 construction have not been satisfactory when used at the lower British Standard limit. A rope of rather solid construction, i.e. 6/19 Seale or 6/25, with as low a tensile strength as the factor of safety will allow gives quite satisfactory results, but ropes of mixed tensile construction may give even better life.

The escape hatch has not been used for the actual release of passengers, but it has been used to effect communication and to reassure them.

The use of trap-door access to the motor room is, from an architectural aspect, generally the most economical, and provided that the motor room is of adequate size, the risk envisaged is sufficiently low to be accepted.

Sound-insulating material is used generally under the winding engine only, but special attention must be given to avoid drumming of the car lining. This is not usually isolated from the car sling.

Mr. Coveney will appreciate that the great advantage of top drive is the reduced weight on the structure, a better rope life and the saving of revenue-earning space. Motor rooms in very exposed positions may call for some local heating of the worm gear, but the controller has never been found to require heat.

DISCUSSION ON "AN ASSESSMENT OF THE IMPREGNATED PRESSURE CABLE"*

Before the North-Western Supply Group *at* Manchester *20th October, the* North-Eastern Centre *at* Newcastle upon Tyne *9th November,* 1953; *the* South Midland Supply and Utilization Group *at* Birmingham *11th January, the* Western Supply Group *at* Bristol *15th February, and the* Southern Centre *at* Hove *3rd November*, 1954.

Mr. E. P. G. Thornton (*at Manchester*): The paper gives a lear-cut factual survey of the design and operational experience f one type of pressure cable. The inclusion of an analysis of roubles encountered is of great value to both cable manu-acturers and users. With reference to the remarks quoted in Section 2.3 regarding the most suitable alloys for use under conditions of vibration, recognition should be given to "E" alloy, which has a high fatigue resistance of $\pm 0 \cdot 41$ ton/in^2. This can safely be used for pressure cable sheaths, since slow creep tests, carried out over a period of five years, at rates of creep as low as $0 \cdot 00005\%$ per hour, have shown an asymptotic value of sheath extension no lower than 5 or 6%. If 1% distension of the

* Brazier, L. G., Hollingsworth, D. T., and Williams, A. L.: Paper No. 1484 S, pril, 1953 (see 100, Part II, p. 641).

sheath occurs before the reinforcement takes the load, this gives a factor of safety of rather more than 4 : 1. Earlier experimental work concerned with slow creep suggested that "E" alloy had a very much lower total extension than the 5% quoted above, but this lower value was, I believe, found to be the result of extrusion technique rather than an adverse quality of the alloy. For conditions of severe vibration, I consider that "B" alloy (having a fatigue resistance of $\pm 0 \cdot 60$ ton/in^2) would be satisfactory.

I agree with the authors' contention that the anti-corrosion serving over the reinforcement of pressure cables is a matter of vital importance. In my view the present answer lies in the use of a homogeneous rubber layer, either extruded or applied in tape form in such a manner that the individual tapes are completely bonded together, the whole rubber layer being subsequently vulcanized to provide the necessary physical strength, abrasion resistance and elasticity. In the absence of long-term field experience with such coverings it is vital to subject all forms of anti-corrosion protection to extremely severe laboratory tests, in which, by continuous measurement of the leakage current through the servings over a large number of heat cycles up to 75° C, freedom from pinholes or even filamentary defects may be assured. A serving temperature of 75° C is not unrealistic, since this is of the order of the maximum temperature attained by the reinforcement when the cable is fully loaded for a reasonable period.

Under such a test p.v.c. tapes tend to exhibit embrittlement due to loss of plasticizer, and it might well be that this plasticizer could have a deleterious effect on the ageing properties of the rubber layer within the serving. For this reason I should feel a little doubtful about the wisdom of including p.v.c. tapes within the servings.

In Section 5.2.4 the authors state that leakages below about 1 litre/min may be ignored. In Fig. 5, which shows the life of a single cylinder when feeding a leaking cable, a leak of 1 litre/min will require the replacement of a cylinder every two days. If such a leak is left indefinitely it must form a very serious nuisance over, say, a 30-year cable life, when cylinder replacements will have to be made something over 5400 times. For all cables (except possibly very long submarine cables), it would seem desirable and practicable to locate and repair leaks of the order of $0 \cdot 1$ litre/min.

In connection with the proposed new joint mentioned in Section 6, I would feel some concern in relying entirely for gas tightness on the internal plumb between the pressure sheath and the sleeve end plate. Notwithstanding the statistical analysis of leaks on double-sleeve and single-sleeve accessories, every cable company must have experienced troubles resulting from porous or badly made plumbs, and the new design of joint is very vulnerable in this respect, since it does not allow a test to be made to establish gas tightness during the installation of each joint. Furthermore, it would appear that difficulties will be encountered in bringing out the gas channel pipes, without at the same time increasing the number of potential sources of leaks.

Dealing with the proposal to design a cable having little or no free compound within the dielectric or intersticial fillers, I am in full agreement with the authors' statement that the a.c. and impulse performance characteristics are in all respects adequate for the design stresses quoted.

In the pre-impregnated gas-filled cable, no free compound exists, and laboratory tests, together with many years' field experience on commercial installations dating back as early as 1937, have shown that such a cable has entirely satisfactory electrical characteristics.

With regard to the pneumatic performance of this type of cable, it will be appreciated that the possibility of obstruction of the gas passage as a result of compound migration, or "frothing" of surplus compound during rapid de-pressurization of the system, is reduced to a minimum.

The following figures, showing the rates of de-pressurizing and re-pressurizing of a gas-filled cable system may be of interest:

(i) 11 000 *yd route length—3 single-core 132 kV cables.*
  (*a*) Time to de-pressurize, 12–16 hours.
  (*b*) Time to re-pressurize, 60–72 hours.

(ii) 8 500 *yd route length—3-core 33 kV cable.*
  (*a*) Time to de-pressurize, 8–12 hours.
  (*b*) Time to re-pressurize, 50–60 hours.

The above figures may be some guide to the authors in estimating the degree of improvement in the pneumatic performance of their cable which may be obtained by removal of all surplus compound from the dielectric and padding spaces. In this respect I should be glad if the authors could indicate by how much the above figures are an improvement on the times of pressurizing and de-pressurizing of the existing impregnated pressure cable, and state whether the draining technique which they propose to adopt will give a pneumatic performance comparable with that of the pre-impregnated gas-filled cable.

Mr. J. H. Pirie (*at Manchester*): It is disappointing that in Section 6 there is no mention of a gas with a high breakdown strength at moderate pressures, such as sulphur hexafluoride, which would go such a long way in reducing the problem of reinforcement.

On the question of operational experience, as I come from the area in which the one and only cable failure has occurred, I will give full marks to the gas pressure cable as being the most suitable one for installation in such districts where ground subsidence can cause such trouble. Any warning such as gas leaks or routine d.c. tests which will avoid service failures are of considerable value.

On the economic side there is no question that with a cable whose insulation is only about one-third that of a solid type the cost per mile will be reduced according to the market price of paper and lead. An additional advantage, however, is the increase in current rating obtained with the thinner dielectric, assuming that the cable is laid in reasonably moist ground with a thermal resistivity below that of impregnated paper.

Mr. J. Banks (*at Manchester*): I notice that in Section 2.1 the authors make certain remarks on the use of screened conductors, and, in particular, to the rather tentative way in which conductor screening has been introduced in this country. I cannot help feeling that the authors themselves are being over-cautious also when they say that an improvement of at least 10% is obtainable in surge and a.c. strength by the use of screening. A fairly extensive testing programme has been carried out on a different type of cable from that stated in the paper, but I think that the results are relevant. We found that by the use of the fairly well-accepted metallized paper as a conductor screen an improvement in surge and a.c. strength of the order of 20–25% can be obtained over the figures given by a standard strand. What is more, we have found no electric strength advantage to be gained from compacting the strand before the screen is applied; this may depend to some extent on the method of compacting used. There is, of course, the economic advantage of compacting. It is interesting to note also that the carbon-paper type of screening material which has been referred to fairly frequently in recent times as a cable conductor screen does not give nearly as good results as a metallized-paper screen. In North America, screening of conductors is used almost exclusively for voltages above 11 kV, and with the improvement possible as indicated by the above test figures, it seems rather

difficult to understand the delay in its general adoption for extra-high-voltage cables.

The paper makes only a very brief reference to the use of aluminium sheaths. Clearly, aluminium as a sheathing material is most attractive in these special types of cable where it avoids the use of an expensive reinforcement. But the authors refer to certain limitations in its present use. Surely these are only temporary, for with the increased availability of aluminium tube of large diameter and long length, together with the rapid development of direct extrusion methods, the economic advantage to be gained from the use of aluminium will bring in fairly quickly its general adoption in place of lead, which has never been altogether satisfactory. With this in mind, one can only feel that the paper should have given a little more information on the aluminium-sheathed cable of the impregnated-pressure type which has already been installed, for it will be of great interest in the future.

The paper deals in Section 2.4 with anti-corrosion protections. Developments are gradually being made in the original rubber bitumen sandwich, and yet the original finish would seem to have a blameless record. Some of the improvements stated must surely result in increased cost, and there is no indication of economic advantages accruing from these developments. In fact, an earlier speaker has recommended fully vulcanized rubber and possibly extruded rubber or synthetic-rubber finishes, which at present must be expensive. It is always difficult to justify developments in a satisfactory article when no economic advantage is to be gained, and I cannot help feeling that much work on cable finishes is being brought along by the increasing acceptance of the saline-bath test as a means of assessing them. This test certainly sets a very high standard for cable finishes, but can we really justify the elimination of cheaper finishes which have been found to be satisfactory?

Mr. L. A. Bates (*at Newcastle upon Tyne*):

Section 2.4. *Anti-Corrosion Protection.*—If one accepts the electrical stability of the cable, its life is truly that of the reinforcement, and whilst to date no reinforcement failures due to corrosion have occurred on the installations reviewed in the paper, I feel that some additional information might be given in order to assess more fully the possible life of the outer coverings. I think that coverings of the type described are not necessarily impermeable at the maximum temperature at which they may be required to operate, so that some information on the loading conditions of the installations under review would be of value. The extra cost of providing a reinforcement more corrosion-resisting than steel might be justifiable in the long run.

2.5. *Electrical Design.*—The design of 33 kV cables based on a maximum stress of 85 kV/cm, which gives an insulation thickness of the order of 0·1 in, is no doubt electrically sound, and a number of installations built to these requirements have been in service for 2 or 3 years. The mechanical weakness of cables with such a thin insulation wall to which the authors refer, makes one question the wisdom of reducing the insulation thickness to this extent. In this connection, I wonder whether the cable failure mentioned in Section 5.1.3, namely of a 0·4 in^2 3-core 33 kV cable (the only cable failure which is recorded in the paper), was built with this insulation thickness. If so, it would seem that such cables would be particularly liable to electrical breakdown if distortion of the cable occurred owing to ground subsidence.

5.1.1. *Joints.*—The improvement of the original joint design arising out of the Burford failures by the introduction of hand-applied paper tapes has, as the authors mention, greatly increased the jointing time, a factor not so important on new installations but certainly so from the maintenance aspect, where the duration of outages must be reduced to a minimum. It is therefore of interest to note that future developments are in the direction of simplifying joint design with a consequent reduction in jointing time.

Referring again to the Burford joint failure, did any explosive disintegration of the joint sleeve take place such as might give rise to dangerous conditions if such joints were exposed above ground or located in buildings?

5.1.2. *Sealing Ends.*—In connection with the flashover of the sealing-end porcelain of the semi-conducting glaze type, can the authors say whether the sealing ends had been periodically cleaned prior to the fault or whether any routine cleaning has been introduced since?

Mr. G. B. Griffiths (*at Newcastle upon Tyne*): I will base my remarks on experience gained in installing and maintaining two impregnated pressure cable installations in the North-East Coast area, and can say that pneumatic troubles were the only sort experienced on these installations. A combination of differential-flow and tracer-gas detecting methods was employed with notable success on two occasions, the former indicating the direction of gas flow to the leak and the latter detecting the point of gas issue. Detection of a leak by the tracer-gas detector does not require ground to be excavated.

The cable passing adjacent to a chemical works area with the ground permeated with coal gas and other gas made detection more difficult, however, but even so conclusive location was obtained in two days and the cable was degassed, the damage repaired, and the cable regassed and in service again after $3\frac{1}{2}$ days. The route length was $1\frac{3}{4}$ miles. No trouble had been occasioned due to compound blocking gas channel pipes in 3-core cables, or causing blockages in s.c. cables. The only inconvenience experienced was that a slightly longer time was taken to regas one circuit at winter temperatures, due to cable compound being more viscous in s.c. cables exposed at terminal poles.

The method of using liquid oxygen to freeze carbon dioxide and so block egress of nitrogen from a gas feed-pipe, thus enabling a gas control valve to be changed, had been used with great success. The time taken was 5 hours, including returning the cable to its normal connection with the nitrogen control panel. This again was done with the cable in service.

Mr. R. H. A. Reid (*at Newcastle upon Tyne*): With regard to the authors' comments on lead sheaths and reinforcements, I feel that fatigue-resistant alloys should be used in all main thoroughfares, in these days of extremely heavy road traffic with its resultant vibration.

In the paper it is also noted that the longitudinal reinforcement has given trouble, and a method of controlling the cable during laying has been devised to tighten this reinforcement. Like Mr. Bates, I wonder whether this is the answer, since, owing to the lay of the longitudinal and circumferential tapes, tightening one will surely slacken the other. Have the authors tried two lighter circumferential tape layers with the longitudinal tapes between them, without packing tapes between these.

With reference to Section 5.4.1, is it not possible to have drainage to a particular level where a fairly sharply defined difference in compounding conditions may be obtained between adjacent sections of the insulation producing a very weak electrical condition at this point? This has been experienced near joints where jointing compound has migrated into the cable, and I think also on normal solid-type cables on terminal poles.

Mr. R. R. Pattinson (*at Newcastle upon Tyne*): The authors refer to the possible use of p.v.c. tapes: this seemed an attractive line of investigation, although samples which I saw recently of a sandwich containing p.v.c. tapes and tested through a relatively small number of heat cycles showed marked loss of nature in the tapes and serious migration of the sealing compound. What

are the difficulties of producing a continuous sheath of thermoplastic material?

The authors have drawn attention to the high breakdown value of wrinkled tapes, and this recalled to my mind the "ribbed" tape developed around 1937 by another cable manufacturer: the claim then made was that a tape ribbed to a certain depth actually increased the breakdown voltage. There seems to be a connection here, but I am sure that the authors do not wish us to draw the conclusion that wrinkled tapes need no longer be avoided in course of manufacture; that indeed would be a retrograde step.

Mr. R. A. York (*at Birmingham*): The authors mention the use of aluminium sheathing; they say that it has the advantage that no reinforcement tapes are required, but I am doubtful whether there is any great advantage in this. The cost of the aluminium-sheathed cable laid and jointed is very little less than that of a lead-sheathed reinforced cable, and it does appear that the thermal resistivity of an aluminium-sheathed cable is higher than that of a lead-sheathed cable, thereby reducing its carrying capacity between 3% and 7%. Can the authors explain this, bearing in mind that it appears that this high resistivity still remains even if the aluminium sheath has been removed and a measurement is taken with copper tape in its place.

On the economics of these cables: is it often necessary to compare impregnated pressure cable with oil-filled cable and to study the economics of the problem? Whereas the impregnated gas-pressure cable might be slightly cheaper in cost, its annual cost is probably higher, since the guaranteed sheath and reinforcement losses are considerably greater than those for an oil-filled cable, and it might well reach the stage where these losses would determine the choice. In view of this, I should like to know whether it would be possible to reduce sheath and reinforcement losses in the impregnated pressure cable without unduly increasing the cost.

Mr. H. M. Fricke (*at Birmingham*): With reference to the flat-type self-compensating cable, I should like to ask the authors whether failure of the lead sheath by fatigue is to be expected in a relatively short life of 10–15 years.

The illustration of the Oilostatic cable shows a metal foil over the stranded conductors. Do the authors consider that this feature gives a worth-while reduction in stress at the conductor surface?

Mr. G. S. Buckingham (*at Birmingham*): The authors admit that the life of the cable is the life of the reinforcement, and is therefore that of the outer protective serving. If we are to enjoy cheap electricity in the future as we have in the past, it is necessary for our capital installations such as power stations and main transmission lines to operate successfully for at least as long after they are paid for as it takes to pay for them. The loan period for these cables is likely to be 40 years, and I think we have every hope that h.v. systems planned to-day may still be serving a useful purpose in 80 or 100 years from now. The question is, Will a rubber serving which is subjected to daily heat cycles and monthly and seasonal variations in temperature and loading be able to retain its flexibility and water-proofing qualities for such a long period?

The frothing of compound on degassing has an important nuisance value. It slows down access to the cable after a fault or after a cable has been damaged. A degassing rate of 2 litres a minute would require about 7 days to reduce the internal pressure of a 3-core cable about 2 in in diameter from 200 lb/in^2 to atmospheric pressure. This is a long time to wait to obtain access to a faulty cable which may be required for commission quickly. Would the authors recommend that gas pressure cables should not be manufactured with pre-impregnated paper insulation which is free from migration problems and would not produce any difficulty during degassing procedure?

Mr. J. S. Woodhouse (*at Birmingham*): The use of oxygen as tracer gas in determining faults does not appear to be a correct principle, if one considers the effect of oxygen upon the core, windings, tank and oil of a transformer. In fact, modern practice is along the lines of exclusion of oxygen from transformers. Surely the same reasoning should apply to these cables, and that active gases, such as oxygen, should be excluded.

Regarding the nitrogen used for pressurizing these cables, are the authors aware that, owing to the gas being made by water-lubricated compressors, the commercial nitrogen is wet to the extent of 0·15 to 1·0 gramme of water per cubic metre of gas at 2 200 lb/in^2, and the oxygen-free nitrogen is wet to the extent of 0·02–0·1 gramme of water per cubic metre of gas at 2 200 lb/in^2. Incidentally, gas made and marketed in the United States, owing to a different method of manufacture, is free from moisture.

It follows that to ensure complete freedom from moisture, the cables should be supplied with nitrogen only via filter-drier equipment; otherwise deterioration of the cable performance is likely to occur.

Mr. H. J. Gibson (*at Birmingham*): Mr. Hollingsworth mentioned that the original experimental cables used compressed air. I am not sure whether that is soluble in oil, but, if not, why should not compressed air be used instead of nitrogen? It is true that the frothing Mr. Buckingham mentioned is caused by the nitrogen dissolved in the oil, and if that is also true of air, my question is already answered. Why did the authors forsake air under pressure and use nitrogen? Further can they not find something that has properties equivalent to nitrogen, except that it will not dissolve in the compound and cause frothing when the pressure is released?

Mr. F. P. Phillips (*at Bristol*): One method of testing for gas leaks involves the injection of air. Does not some of this remain and cause deterioration of the insulation? Is a length of cable damaged when the gas escapes suddenly, owing to mechanical damage, under such conditions that the removal of gas pressure precedes the removal of electric pressure?

Mr. A. G. Milne (*at Bristol*): Not long ago, I carried out an investigation into the economics of the use of 33 kV solid, oil-filled, and impregnated gas-filled cables, and came to the conclusion that at 33 kV the solid cable was the most economical.

The comparison of the cables was based on an equivalent load-carrying capacity of approximately 20 MVA, for which a 0·3 in^2 solid cable would be necessary as against a 0·25 in^2 gas-pressure cable. As a result, the capital cost and consequently the capital charges of the gas cable would be lower, but when the losses were taken into consideration the circumstances were reversed and the solid cable showed an economy.

With the sizes of cable considered, the losses of the gas cable were about one-third greater than those of the solid cable, and when these were capitalized it was found that the total costs were less for the solid cable.

The authors have mentioned that the use of aluminium sheathing in place of lead was being considered for gas cables. While this might effect a saving in first cost, as the resistance of the aluminium sheathing would be less than that of the lead, the sheath losses on the former would be greater, and after capitalizing the losses it was probable that the overall costs of the aluminium-sheath and lead-sheath cables would not be very different.

Mr. E. H. T. Jewell (*at Bristol*): The pneumatic accessories required for successful operation of a cable dielectric working at 200 lb/in^2 introduce many complications into such an installation, and I am not at all sure that such complications are justified for 33 kV cables. However, on 132 kV and 275 kV systems, where the pressure design affords a safe working stress at the

onductor of 100 to 110 kV/cm, cable dimensions can be kept ithin reasonable limits from the handling points of view, ereby amply justifying the complication of ancillary equipment.

With regard to the third paragraph of Section 2.1, I should ke some information as to possible discrepancy between otentials on conductor and metallized-paper screen.

In Sections 5.1.1 and 3.1 it is implied that hand-applied pre-npregnated paper tapes are electrically superior to a machine-pplied paper roll, and yet in Section 3.1 the reverse might seem be the case; this point might well receive some clarification.

From the text immediately following Table 3, it seems that a ress cone and condenser cone are both used in the 275 kV rmination. In Table 4 no stress cone is mentioned, and I ould like to be informed whether in fact it has been omitted.

During its normal life a pressure cable may be subjected to equent depressurizing. Consequently, the mass-impregnated ielectric will lose varying though appreciable amounts of npregnating compound, and it may become necessary to rovide some means of determining the consequent increase in ermal resistance.

As the authors have maintained, there seems to be no longer the eed for proving the cable by the application of excessive a.c. ver-voltages, so long as the impulse test requirements can be et. However, the inherent high capacitance of this product troduces considerable difficulties in the generation of the steep-onted impulse waves to be applied during tests.

Damage from ground subsidence, recorded in Section 5.1.3, ises a question as to the possible effects of cable movement, llowing a pressurized condition for a number of years. From e records of this incident, there would seem to be no reason to ttribute the resulting electrical failure to weakness in mechanical esign. It would be interesting, however, to know the behaviour f an aluminium-sheathed pressure cable under similar con-itions. It might well be that this type would give a better erformance where ground subsidence is likely to be encountered.

Mr. E. K. Dalby (*at Hove*): With reference to the arrangement f the cores in the standard 3-core straight joint, as shown in ig. 1, the adoption of the inverted pyramid formation is a ost refreshing exception to the average manufacturer's rule, nd as far as solid cables are concerned I regard this as very nportant. Where, as is usual unfortunately, the cores are own in pyramid formation, with minimum clearance between e top core and the highest part of the lead sleeve, an area kists which is more likely to contain voids and discontinuities an any other similar area, and it is also subjected to the highest ossible electric stress.

The voids are concentrated here owing to effects of gravity d convection; discontinuities are liable to occur as a result of pping up. It is extremely difficult to guarantee the elimination these effects, irrespective of the means adopted in solid-cable inting techniques. The relief of electric stress in the vulnerable ea is achieved by the inverted pyramid arrangement.

The contriving of this arrangement in core-to-core jointing is mple for the skilled jointer, although he is usually under the npression, due I think to misguided instruction, that he must ot interfere with the fortuitous arrangement of cores as they ise in practice. The principle behind this instruction is sound, t it is quite impracticable, since the chances of a perfect match tween cable ends to be jointed are very remote; the jointer ust interfere with core arrangement in the vast majority of ses, and this can be done with no more distortion resulting an is due to the normal bending and setting of the cores. The telligent use of, and if necessary the curbing of, the natural of the cores can swing them through an arc of up to ±60° thout damage to insulation.

Turning to the profile of the stress cone as illustrated in Fig. 1, I am surprised at the small divergence from normal, and further surprised that at the extremity a longitudinal stress of 1·5 kV/cm is not exceeded. Has it ever been considered desirable to eliminate longitudinal stress almost completely? Presumably this could be achieved by curling the stress cone back on itself. As the ratio of electrode surfaces to spacing is extremely large, the profile of the curl could take the form of a very small semi-circle. I appreciate that practical considerations usually out-weigh the advantages of field uniformity at the surface of the stress cone.

Finally I would comment upon the formula $4 \cdot 5(E + 10)$ upon which the B.E.A. impulse requirement is based. For screened-type cable I think that E would more logically represent peak phase voltage than r.m.s. line voltage, the constants to be adjusted accordingly. For lower voltages I consider the require-ment to be very conservative; I have tested many scrap lengths of 11 kV cable with applied surges of 200 kV without apparent adverse effects.

Mr. L. H. Fuller (*at Hove*): The authors omit one of the major factors in any assessment of an engineering problem—namely the economic factor. They only mention economics once by saying that 33 kV is the lowest economic voltage by comparison with the solid-type cable.

By inference, Table 1 confirms that the cable is an economic proposition, as it lists 15 installations with a total of 111 000 yd at 33 kV, and 15 with a total of 125 000 yd at 66 kV; yet I find myself in a difficulty, as on the only occasion when I was associated with the relative merits of 33 kV oil and gas cables (in 1950) I found that, although the prices for the two types were virtually the same for the same size of conductor, the capacity of the gas cable was less, so that economically on this occasion it lost. Accordingly, I should like to know what the economic assess-ment is for 33 kV gas and oil cables, and if unfavourable, whether it can be contended that the gas cable has certain advantages over other types which warrant its use. I know the authors take care to make no comparisons other than with solid cable—and indeed draw attention to the fact—but it seems to me that no assessment can be complete without some mention of economics.

Mr. H. Diggle also contributed to the discussion at Man-chester, **Messrs. H. S. Davidson** and **R. Mallet** to the discussion at Birmingham, **Messrs. W. H. Campbell** and **G. Evans** to the discussion at Bristol, and **Mr. A. L. Ashton** to the discussion at Hove.

Dr. L. G. Brazier, Mr. D. T. Hollingsworth and **Dr. A. L. Williams** (*in reply*): It was not our purpose to compare the impregnated pressure cable with other types. No type is yet perfect, and it is easy to select points of superiority in one or another and to argue solely on those. In sound design, however, attention must be given to the weakest points rather than the strongest. We have presented the case for one particular design, and the completeness of the presentation has been confirmed by the fact that no contributor to any of the discussions has brought forward any service incident not revealed in the paper. It is necessary to await corresponding disclosures on other types before any valid comparison can be made.

On the question of economics, differences between cable types are small and, moreover, are continually varying because of fluctuations in the material costs which make up such a high proportion of the whole. Also, each installation must be con-sidered separately, because the length and nature of the route determine the drum lengths which can be employed, the number of electrical accessories, the disposition and degree of elaboration of the non-electrical accessories, etc. These and other factors make a general treatment of the first cost impossible, even without the complications of capitalization of losses, cost of outages and so on.

It is convenient to deal with a number of points according to the component of the cable to which they refer.

Conducting Screening.—The ideal conductor screen would transform the stranded conductor of the cable into a perfectly smooth conducting cylinder, the surface in contact with the dielectric being at the same potential as the conductor itself. Existing theory then predicts a considerable alleviation in the electric stress to which the dielectric is subjected. There is now considerable evidence that the theory is not applicable to oil-impregnated paper cables, at least in so far as impulse conditions are concerned, and that the practical advantage of conductor screening under such conditions is quite small. In consequence, we adhere to the 10% improvement which we claimed in the paper.

Dielectric.—From practical experience, there are no grounds for believing that a dielectric is made less vulnerable to mechanical damage by making it thicker, and we have no fears whatsoever about the dielectric wall of 0·1 in, approximately, which has always been used in 33 kV cables. Paper has little elasticity, and good mechanical performance in a lapped dielectric depends on the tapes sliding one over the other. If there is any resistance to free movement, wrinkling of the paper occurs on bending, particularly in factory handling before the cable is impregnated. This is, in general, a condition which is easier to avoid with a thin dielectric wall than with a thick one, but there are complicating factors such as type of paper, method of application, type of impregnant, size of conductor, etc. So far as we are aware, simple wrinkling has no measurable electrical effect, but as it can give rise to doubts or cause argument, it is best avoided as far as possible.

There is nothing inconsistent in claiming advantages for hand-applied paper tapes in joint construction whilst at the same time maintaining that machine-made dielectric is electrically superior. In a joint, the point of least strength is the interface between the original cable dielectric and the reconstituted joint dielectric. It is quite impossible to obtain a good fit with a machine-made paper roll, and the individual fitting of tapes by hand results in a stronger product.

Some doubts have been expressed about the possible harmful effects of traces of oxygen in the dielectric. In fact, the gas cable is relatively insensitive to this in moderation, and there is no need to take rigorous and expensive precautions to exclude it entirely. Recently an opportunity arose to examine a short length of one of the earliest cables installed (and, incidentally, one of the most heavily loaded), which became available through a diversion. The chemical constitution of the dielectric was examined by the most critical analytical methods and no significant change was revealed.

Experimental cables have been made with gases of higher electric strength, such as sulphur hexafluoride, but their performance has been disappointing, and the extra expense has not been considered justified.

It is difficult to imagine circumstances in which severe damage to the cable permits a sudden release of gas without also causing direct mechanical damage to the dielectric. The only known case of sudden fall in pressure is that described in Section 5.1.2, where a porcelain insulator, connected to only a short length of cable, failed. There was no apparent damage to the cable, and it is still operating satisfactorily. It must be realized that the gas in solution under pressure in the dielectric, although making itself a nuisance under some conditions, also provides a safety reservoir which comes into operation spontaneously if the free gas pressure falls.

Regarding the thermal resistance of the dielectric, any changes through compound movement are insignificant and have no appreciable effect on the temperature of operation. The higher thermal resistivity of thin walls, which at one time appeared to be connected with the use of the aluminium sheathing process, has been investigated more thoroughly, and although the exact reason for it is still obscure, it is definitely not related to the sheath material or its method of application.

Sheath.—The simple truth about the choice of lead alloy for the sheath is that the ideal material, which would combine very good fatigue properties with very good extensibility at low creep rates, does not yet exist. We know of no competent metallurgist who is prepared to state a positive preference for any one alloy, and the choice must still be based on judgment, backed by service experience. Whether any of the newer alloys with arsenic and tellurium will prove advantageous remains to be seen, but this is under investigation. In any case, lengthy trials would be necessary before a wholesale change-over could be made with confidence.

This is a technical reason for the introduction of aluminium sheathing, but it is so far available only in comparatively short lengths, necessitating more joints and reducing the economic advantage, which cannot be fully realized until longer lengths can be produced (for example, by direct extrusion).

Reinforcement.—Much thought has been given to reinforcement design, but no case can be found, on either technical or economic grounds, for changing the present arrangement. Whether the longitudinal reinforcement is absolutely necessary in buried cables is uncertain, but it has not yet been found possible to develop an experimental procedure for settling the matter beyond question. Unfortunately, very little is known about the movements which take place in cables buried in different soils and with widely varying load conditions, and it is judged better to retain the present construction, despite the occasional mishaps which occur. It should be noted that the present design takes no account of the longitudinal strength of the conductor, and this is an aspect which merits further examination, because it might be possible to reduce or omit the longitudinal reinforcement.

Anti-Corrosion Protection.—This is a subject which is not specific to the impregnated pressure cable. No engineering material is corrosion proof, no protective medium is everlasting, and no accelerated laboratory test has ever been devised which makes possible a forecast of life and performance under conditions of soil burial. For the time being, therefore, serving design is based on the advice of corrosion experts. Vulcanized rubber is at least a material which is supported by much experience and which has not yet been found wanting. Extruded plastics are now coming into fashion, and they look attractive at first sight, but it must be realized that it is not yet possible to bond them to the cable to be protected, so that, if mechanical damage or deterioration of the serving occurs, the results could be much more widespread than in conventional servings, which invariably have an adherent coating of bitumen directly over the sheath or reinforcement. There is what appears to us to be an unfortunate tendency to place too much reliance on highly artificial tests (e.g. the saline bath test), which bear no recognizable resemblance to service conditions.

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AN EXAMINATION OF HIGH-VOLTAGE D.C. TESTING APPLIED TO LARGE STATOR WINDINGS

By R. T. RUSHALL and J. S. SIMONS, B.Sc.(Eng.), Associate Members.

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SUMMARY

The merit of a proposed non-destructive method of assessing the reakdown voltage of stator-coil insulation by means of high-voltage lirect current is examined. The proposal is to measure the steady-tate leakage current at successive increments of applied voltage and redict a breakdown value from the trend of the plotted results.

Laboratory tests applied to a range of specimens of sheet insulation, ncluding a number with artificially-formed faults, indicate that the nly breakdown which can be predicted by this method is that across ir paths external to the specimen.

Tests carried out on a complete high-voltage stator winding and on ingle stator coils give similar results. No assessment of slot-insulation quality is possible: the only increase in current, suggestive of pproaching failure, results from end-winding leakage and discharge ffects. Surface contamination of the end-winding and even quite xtraneous discharges, when present, have a marked influence on the urrent measurements.

It is concluded that the high-voltage d.c. method of testing investi-ated has no valid basis for non-destructively indicating the service-bility of the insulation of high-voltage machines.

(1) INTRODUCTION

The over-potential proof-testing of machine insulation with lternating current is the recognized method of test both in this ountry and in America.[1,2] Recently, however, much attention as been given in America to the use of high-voltage direct urrent for this purpose.[3,4] This has led in turn to the intro-luction[5,6,7] of a high-voltage d.c. test as a means for estab-ishing insulation quality non-destructively, since it is claimed hat the direct-current/voltage relationship often enables a rediction of breakdown voltage to be made.

The use of direct current at voltages up to one or two kilo-olts for testing insulation quality, primarily dryness, of a.c. nachine insulation is well established, but over-potential testing vith direct current introduces many factors which need con-ideration.

One factor is the relation between d.c. and a.c. severity. A .c./a.c. (r.m.s.) voltage ratio of about 1·6 has been suggested[8] or equal effectiveness, although its value is shown to be variable, epending very much upon the nature of the insulation under est. Thus, there may always be doubt as to whether a winding ested on this basis is being under- or over-stressed. Stress istribution, particularly over the end-windings, is very different n the two cases, being governed principally by surface resistance vith direct current, and principally by capacitance with alternat-ng current.

One reason for advocating d.c. testing is the claim[8] that a.c. esting causes greater deterioration of the insulation—depending n its condition and on the value and time of application of the lternating over-voltage. Another is that testing equipment aving a low current rating can be used.

But examination of the evidence presented[8] shows that the amount of deterioration likely from normal alternating over-potential tests curtails the life of a winding by an altogether negligible amount, and however convenient d.c. testing may otherwise prove, it is first necessary to be certain that it can really achieve its object.

This paper is therefore concerned with this aim—to examine the validity of high-voltage d.c. testing, particularly in relation to the claim that it can afford a non-destructive means for predicting breakdown.

The test requires the measurement of the steady-state leakage current between winding and core at successive increments of test voltage up to a maximum of about twice the alternating test voltage (r.m.s.) of the machine (i.e. up to 46 kV d.c. for a new 11 kV machine).[6] If the breakdown voltage of the weakest point of the winding lies within this range, it is said that this will be revealed by a sudden trend towards high current and low resistance.

If valid, such a test method has attractive features, so that a natural desire to examine the claims, as well as inconsistencies, reported by various investigators, led to the present investigation in which material samples, individual stator coils, and also a complete machine winding, were examined from the viewpoint of breakdown prediction by d.c. testing.

(2) TEST EQUIPMENT

A direct voltage adjustable between 0 and 100 kV was obtained by rectifying the output of a high-voltage 50 c/s testing transformer, using the arrangement shown in Fig. 1. An appropriate

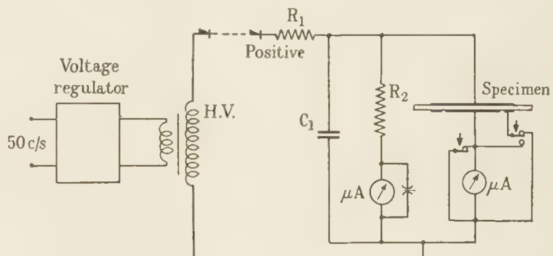

Fig. 1.—Test circuit.

$R_1 = 5\,\mathrm{M}\Omega$, $C_1 = 1\,200\,\mu\mu\mathrm{F}$.
$R_2 = 160\,\mathrm{M}\Omega$.

number of selenium-type rectifier units of 5 kV, 5 mA rating, were connected through a 5-megohm limiting resistor to the smoothing capacitors.

Direct voltage was measured by a calibrated microammeter in series with a 160-megohm resistor. Current was measured on the low-voltage side of the specimen, usually with a reflecting-type microammeter having a maximum sensitivity of 0·05 μA/cm and capable of detecting 0·005 μA. Arrangements were made for the measurement of both l.v. centre-electrode current and

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the combined l.v. centre-electrode and guard current. Except for the intermittent periods of measurement, both the l.v. electrode and guard were directly earthed.

Preliminary tests demonstrated the major importance of preventing corona discharge in the vicinity of the measuring circuit, and for this reason high-voltage connectors of adequate diameter, and screened measuring leads, were employed.

(3) SHEET MATERIALS

Several materials of normally good dielectric quality were subjected to the high-voltage d.c. test in order first to provide a basis of comparison for the behaviour of defective specimens in subsequent tests, and secondly to investigate the claim[9] that a good prediction of the breakdown voltage of uniformly sound insulating materials is possible by this method of testing. The materials considered were mostly those used in stator-coil insulation and included mica splittings, of both clear stained-ruby muscovite and dark-brown phlogopite varieties, shellac-bonded micafolium, and black varnished cloth.

Two forms of tests have been made—one in which the voltage stress was applied through the material and the other in which the stress was applied along its surface. The former has been termed the volume-leakage, and the latter the surface-leakage, test, although in the latter case effects other than simple surface conduction were involved.

All tests were carried out at a temperature of approximately 20°C and without special conditioning, unless otherwise stated.

(3.1) Volume Leakage Tests

(3.1.1) Specimens and Test Procedure.

The materials were each represented by two or more specimens of different thicknesses. Those of the two varieties of mica were large single splittings having a minimum surface dimension of 7in, taken in each case from the same block of virgin mica. The micafolium specimens were obtained by carefully splitting hot-pressed shellac-bonded micafolium sheet into pieces of the desired thickness. The black varnished cloth specimens consisted of one or more layers of a standard 7mil thick material. Specimens of up to 24in square of the latter two materials were used in order to reduce surface leakage. For this reason also, a number of the tests were carried out with the specimens immersed in transformer oil.

In making each test, the specimen was placed between 2¾in diameter (h.v.) and 2in diameter (l.v.) flat electrodes; the latter, being the measuring electrode, was surrounded by an annular guard of 2¾in outside diameter. Tinfoil was used to improve electrode contact.

Voltage was applied and increased in steps of appropriate magnitude, allowing a sufficient period at each step, usually of 3min duration, for the current readings to become constant. This procedure was continued until failure took place.

(3.1.2) Test Results.

It was found that one or more specimens of all groups failed by puncture to the guard. Consequently the total currents have in all cases been plotted so as to provide directly comparable results taking due account of any current associated with approaching failure. However, measurement of both centre-electrode and total currents was useful in providing some indication of the distribution of current, and by inference, of extraneous surface and edge effects.

(*a*) *Single Mica Splittings.*—In Fig. 2 the steady-state total-current measurements obtained on both muscovite and phlogopite mica specimens, when tested under oil, are plotted against the applied voltage. In these tests the centre-electrode and total

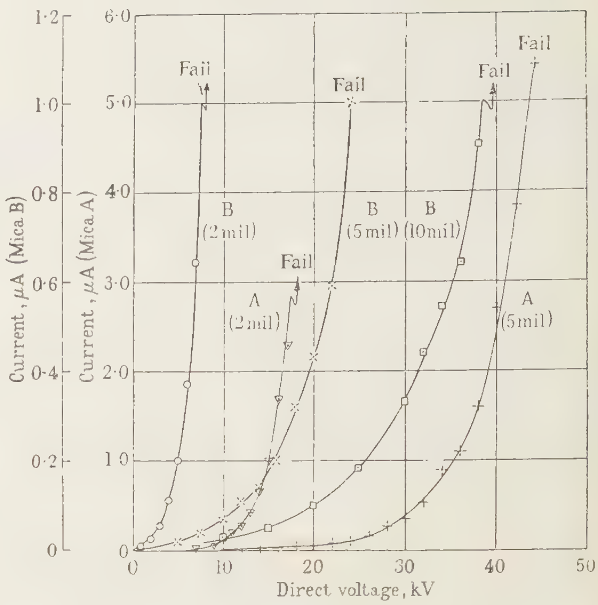


Fig. 2.—Current/voltage characteristics.
A: Clear stained-ruby muscovite.
B: Dark-brown phlogopite mica specimens.

currents proved to be proportional to the corresponding electrode areas, thereby indicating an absence of surface leakage effects.

In Fig. 3 the dimensional effect of thickness is eliminated by plotting the equivalent conductivities to a logarithmic scale

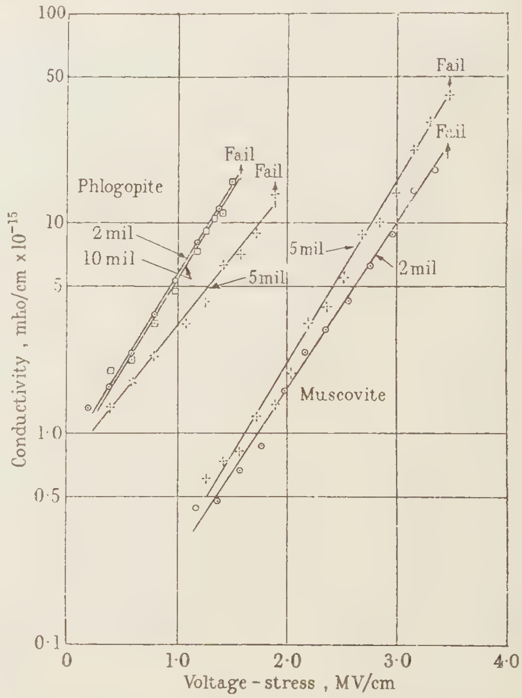


Fig. 3.—Conductivity/voltage-stress relationships for clear stained-ruby muscovite and dark-brown phlogopite mica specimens.

against voltage stress. The close agreement between the curves of the respective groups tends to confirm that a true conductivity of the material is represented. Also the linear relationship between conductivity and applied stress strongly suggests an

ordered process of conduction, continuous up to the breakdown voltage.

Consideration has been given to the possible heating effect of the energy losses involved in this series of tests. On the reasonable assumption that these losses were uniformly distributed, only with the muscovite mica specimens may such an effect have been significant. Facilities for thermal dissipation were generally good, and even with these specimens there was no evidence of heating or of any increase in current during the 3 min period at the voltage immediately preceding failure. It is therefore considered that in all these cases the influence of thermal effects on the observed changes in conductivity can be dismissed as insignificant.

(*b*) *Micafolium.*—Results obtained on the micafolium specimens are given in Fig. 4, some tests being made in air and others

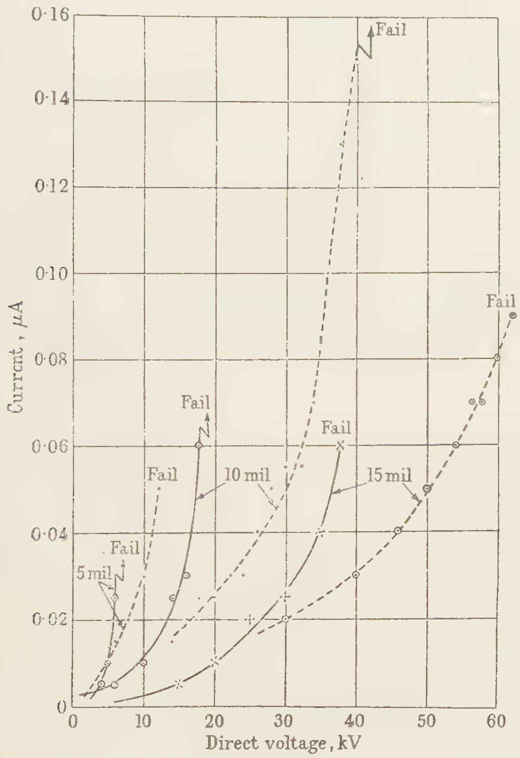


Fig. 4.—Current/voltage characteristics of pressed micafolium sheet.
——— Tested in air.
– – – Tested in oil.

in oil. With this material the ratio of the centre-electrode current and total current differed with the different specimens, and sometimes suggested surface leakage. However, this was not supported by the fact that much lower readings were obtained at the same voltage on thicker but otherwise similar specimens. The inconsistent behaviour experienced is attributed largely to the irregular structure of this type of material. It is of interest to note that the observed currents immediately preceding failure were much lower than with the homogeneous mica splittings.

(*c*) *Black Varnished Cloth.*—Results for several specimens of black varnished cloth are given in Fig. 5. When tested in air, a consistent surface or edge contribution to the current—representing roughly one-third of the total current—was experienced. This contribution was reduced to an insignificant proportion in tests made on similar specimens in oil.

In testing this relatively absorbent undried material, moisture may well have had a significant effect upon its behaviour. A

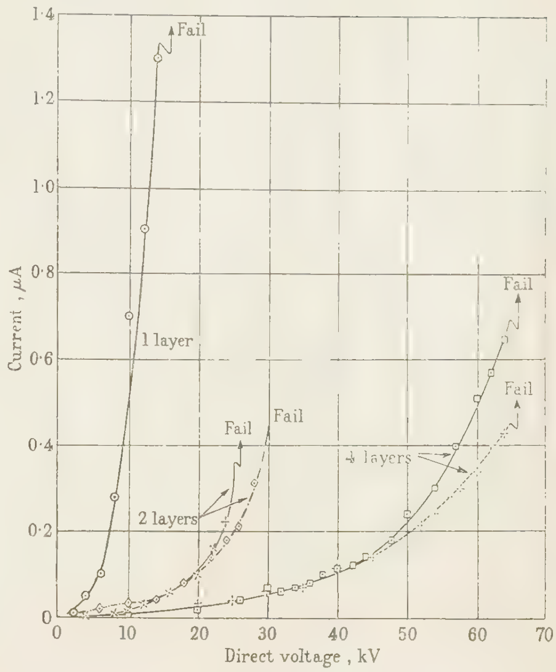


Fig. 5.—Current/voltage characteristics of single and multiple layers of 7 mil black varnished cloth.
——— Tested in air.
— — — Tested in oil.
— · — · Dried 8 hours at 110°C; tested in oil.

further test was therefore made upon a specimen consisting of two layers of material thoroughly dried at 110°C immediately before being immersed and tested in oil. This gave the results shown by the chain-dotted curve in Fig. 5. It is evident from this that the rising form of curve is characteristic of the basic material, apart from any added contribution of moisture which normally may have been present.

(3.1.3) Comments.

In general, the plotted curves, which provide a clear record of the changing conductance of the materials to the point of breakdown, are characterized by an absence of any sudden change in slope indicative of approaching failure.

Prediction of breakdown voltage in the course of obtaining such results is impracticable, except perhaps with very thin specimens. Much depends upon the choice of co-ordinate scales; however, these cannot be decided upon without previous experience of the behaviour of the material involved.

In an alternative form of graph used by some investigators of this test method, insulation resistance instead of current is plotted against test voltage. This is said to predict failure at or near the point of intersection of the extrapolated curve with the voltage base.

The results obtained on the black varnished cloth specimens when plotted in this manner give the curves shown in Fig. 6. It is evident from these that the breakdown value cannot be predicted with accuracy by extrapolation. Thus a somewhat extended rise in current, as experienced with the 7 mil specimen, produces an equivalent flattening of the resistance curve which makes any prediction very doubtful. It will be appreciated in this case also, that the choice of co-ordinate scales can have a marked influence on the apparent implications of the curves. In general, it would seem that the resistance form of curve has no real advantage over the current/voltage curve, and indeed neither form can be relied upon to predict breakdown.

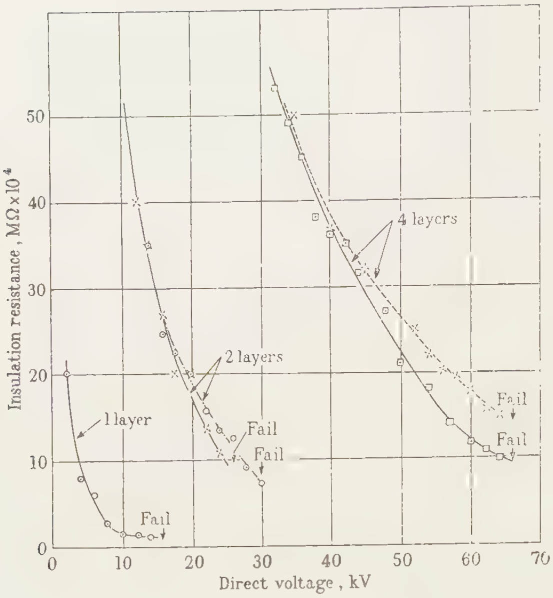


Fig. 6.—Insulation-resistance/voltage curves of 7 mil black varnished cloth specimens.

——— Tested in air.
— — — Tested in oil.
— · — · Dried 8 hours at 110°C; tested in oil.

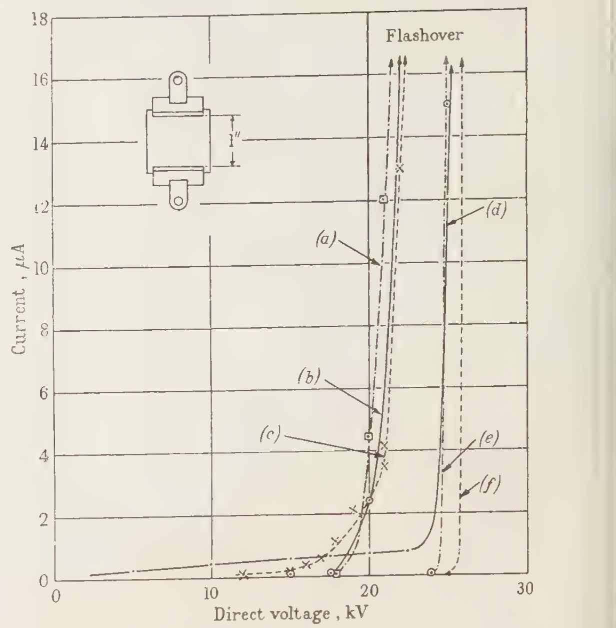


Fig. 7.—Surface leakage-current/voltage curves of sheet insulation tested in air.

(a) Air only (flashover voltage 23 kV).
(b) Black varnished cloth (flashover voltage 25 kV).
(c) Phlogopite mica (flashover voltage 25 kV).
(d) Paper (flashover voltage 27 kV).
(e) Micafolium (flashover voltage 26 kV).
(f) Muscovite mica (flashover voltage 26 kV).

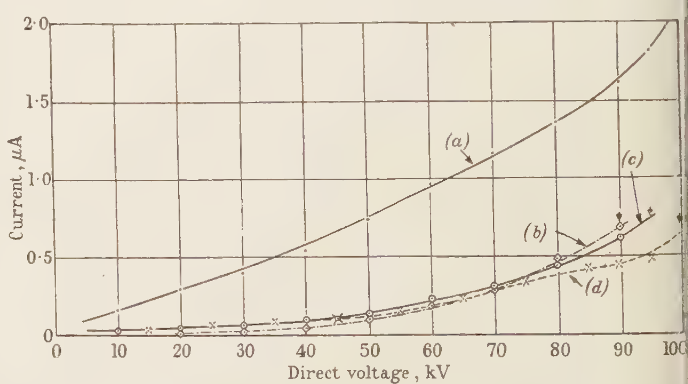


Fig. 8.—Surface leakage-current/voltage curves of sheet insulation tested in oil.

↓ Initial flashover.
(a) Paper.
(b) Micafolium.
(c) Black varnished cloth.
(d) Clear mica.

(3.2) Surface-Leakage Tests

(3.2.1) Specimens and Test Procedure.

In making surface-leakage tests an electrode arrangement similar to that used by Johnson and Clokey[9] was employed. No attempt was made to guard the measuring electrode, as it was intended that all current passing between electrodes should be recorded.

The test specimen consisted of a single piece of the material, $1\frac{1}{2}$ in square. This was gripped between spring-clip electrodes $1\frac{3}{16}$ in wide, spaced 1 in apart, as shown in Fig. 7. Voltage was applied in steps, and current readings were taken as in the volume-leakage tests. Normally the tests were carried out in air, but for comparison purposes, a further group of specimens were tested in oil.

(3.2.2) Test Results.

The measurements obtained on specimens tested in air are presented in Fig. 7. The characteristic feature is a considerable and rapid increase in current over a relatively small voltage range at about 20–25 kV, culminating in failure owing to flashover between the electrodes. The specimens were essentially undamaged and withstood re-application of voltage. In some cases, current instability preceded the marked increase in the steady current recorded.

In the tests made under oil the current increased at a relatively low and steady rate to voltages of 90–100 kV as shown by the results in Fig. 8; flashover under oil occurred in some cases as indicated.

(3.2.3) Comments.

An apparently good prediction of failure is afforded by a surface-leakage test of the type described, when made in air. However, the marked increase in current leading to this prediction is primarily the result of gaseous discharge, and the failure so predicted is that of the air, modified but slightly by the presence and nature of the specimen. Confirmation of this is afforded by the almost identical curve included in Fig. 7, which is based on quite stable currents, obtained upon air alone, and also by the consistency of the several failure voltages. These are recorded in Table 1 together with comparable values abstracted from Reference 9. The absence of any inordinate current rise in tests made in oil emphasizes the dependence of the earlier results upon the ambient medium.

Although the "prediction bend" and failure are shown by these tests to be essentially independent of the insulating material involved, in practice, surface contamination may well alter the stress distribution and increase the significance of surface conductivity, thereby affecting the abruptness of the bend in the current/voltage characteristic. This is demonstrated in Section 4.2. It is also likely that electrode contour and spacing will influence the relationship between the onset voltage of the leakage-discharge phenomenon and that of ultimate failure.

Table 1

SURFACE-FAILURE VOLTAGE OF SPECIMENS TESTED IN AIR BETWEEN CLIP ELECTRODES, AT 1 IN SPACING

Authors' test results		Results abstracted from Reference 9	
Material	Failure voltage	Material	Failure voltage
	kV		kV
Muscovite mica ..	26	Mica splitting:	
Phlogopite mica ..	25	*Dry*	25
Micafolium	26	*Humidified*	21
Black varnished cloth ..	25	Black varnished cloth:	
Untreated paper (wood-pulp 0·007 in thick)	27	*Dry*	25·5
		Humidified	24
Air	23	Phenolic-alkyd varnished	
	27·5	cloth:	
		Dry	18
		Humidified	18
		Silicone-rubber-reinforced glass cloth:	
		Dry	27
		Humidified	25

(4.1) Defects in Insulation stressed Normal to Surface

Flat-sheet specimens were made, consisting either of shellac-bonded micafolium sheet, multiple layers of black varnished cloth or, in one case, a combination of both.

Each specimen embodied defects in one of the following forms:

(*a*) Complete perforations.
(*b*) Recessed holes.
(*c*) Staggered holes with interlayer creepage paths.
(*d*) Enclosed voids.
(*e*) Unbonded mica flakes.

The defective specimens were tested between the guarded flat-disc electrodes described in Section 3.1.1, with the defect centrally placed underneath the centre measuring electrode—except in specimen (*e*) in which the defect extended over the whole area. Specimens of types (*a*), (*b*), (*c*) and (*e*) were tested in air, and those of type (*d*) in oil; all tests were made at room temperature. Details of the individual specimens and defects, together with a brief record of the test results are given in Table 2. These are supplemented where necessary with graphs of the test results and a sketch of the defect showing, at X, the position of failure.

Table 2

VOLUME-LEAKAGE TEST RESULTS ON SPECIMENS EMBODYING DEFECTS DIRECTLY BETWEEN ELECTRODES

Specimen	Material	Defect	Break-down voltage	Comments
			kV	
(a_1)	Micafolium board, 62 mils thick	Four holes right through, $\frac{1}{16}$ in dia.	6	Unpredictable breakdown
(b_1)	Micafolium board, 62 mils thick	Four recessed holes, $\frac{1}{16}$ in dia. × 0·056 in deep	76	See Fig. 9; considerable surface leakage Unpredictable breakdown
(c_1)	Micafolium board Outer layers, 7 mils thick Centre layer, 15 mils thick	Four staggered holes, $\frac{1}{16}$ in dia.	16	Lateral breakdown between holes; unpredictable, maximum current, 0·005 μA
(c_2)	Black varnished cloth Outer layers, 7 mils thick Centre layer, 14 mils thick	Four staggered holes, $\frac{1}{16}$ in dia.	24	See Fig. 10; puncture of outer layers, unpredictable breakdown
(c_3)	Black varnished cloth with micafolium reinforcement	Four staggered holes, $\frac{1}{16}$ in dia.	24	As for Specimen (c_1)
(d_1)	Micafolium board, 24 mils thick	Nine enclosed voids, $\frac{1}{4}$ in dia. × 0·014 in deep	19	See Fig. 11; unpredictable breakdown
(d_2)	Micafolium board, 34 mils thick	Nine enclosed voids, $\frac{1}{4}$ in dia. × 0·014 in deep	52	See Fig. 11; unpredictable breakdown
(e_1)	Mica splittings in layer 20 mils thick, cover papers 5 mils	Loose mica splittings	16	See Fig. 12; unpredictable breakdown
(e_2)	As for (e_1), except for 30 mils layer of splittings	Loose mica splittings	48	See Fig. 12; increase of guard current at 46 kV—probably due to surface leakage

Size of specimens, except (c_1) and (c_2): 12 in square approximately; specimens (c_1) and (c_2) were 24 in square.

(4) ARTIFICIAL FAULTS

To be effective the test must provide unmistakable evidence of any dielectric weakness, whether distributed or local, which is capable of causing a significant reduction in breakdown voltage. Therefore, in order to explore the reliability of the method in this respect, tests have been made on laboratory specimens of insulation, embodying deliberate faults in various forms. The extent of the defect in relation to the area of the specimen was such as greatly to exaggerate its influence, compared with that of a comparable defect in the much more extensive insulation of a machine winding.

For convenience the defects are grouped under the headings

(*a*) Defects in insulation stressed normal to the surface.
(*b*) Defects leading to surface failure.

Fig. 9 records results obtained on specimen (b_1) containing deeply-recessed holes. No suggestion of forthcoming failure is provided by the pertinent centre-electrode current curve. For comparison, the total currents are plotted in order to demonstrate surface-leakage or edge effects; however, the current increase due to these effects was in no way associated with the breakdown experienced.

With specimens (c_1) and (c_3) containing staggered perforations —which failed by lateral breakdown between layers—the current preceding failure did not exceed the minimum detectable by the microammeter. With specimen (c_2) which failed by puncture, breakdown was unpredictable, as is evident from Fig. 10.

Similarly unpredictable failures occurred with specimens (d_1) and (d_2) containing voids, as shown by the curves in Fig. 11.

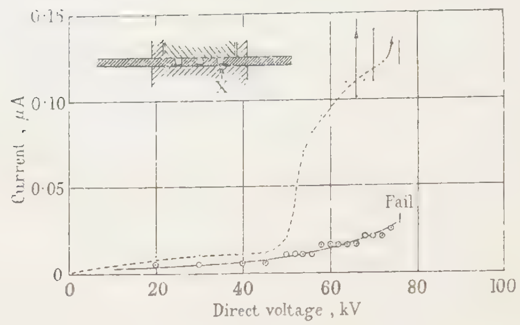


Fig. 9.—Micafolium specimen (b_1) containing recessed holes.
——— Centre-electrode current.
— — — Total current.

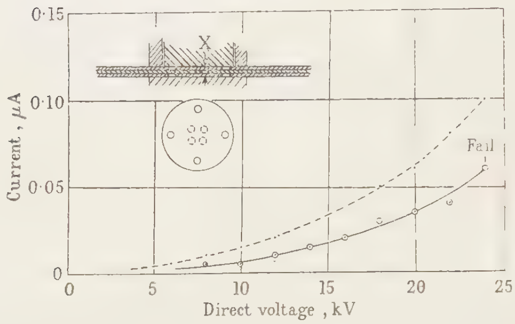


Fig. 10.—Black varnished cloth specimen (c_2) containing staggered holes.
——— Centre-electrode current.
— — — Total current.

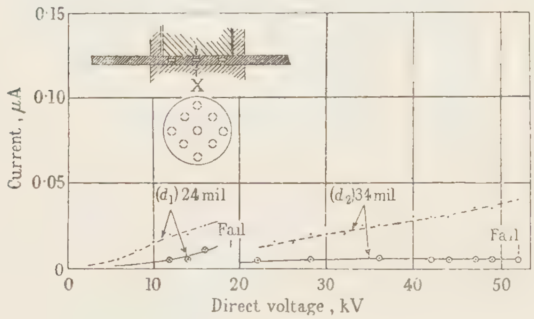


Fig. 11.—Micafolium specimens (d_1) and (d_2) containing internal voids.
——— Centre-electrode current.
— — — Total current.

In the case of specimens (e), which consisted of loose mica flakes spread in a layer between supporting sheets of undried paper, current measurements were obtained, as recorded in Fig. 12. Failure resulted from puncture to the guard ring. It was preceded by some increase in the total current, but at the voltage in question, 45 kV, this increase may well have been caused by the onset of surface or edge effects as suggested by the total-current curve in Fig. 9.

Considered collectively, the results of this group of tests show the defects to have reduced very considerably the breakdown value of the material involved. This follows, in most cases, from comparison with breakdown values recorded in Section 3.1. Although currents somewhat higher than are likely to occur with sound specimens are sometimes obtained, in no case has the

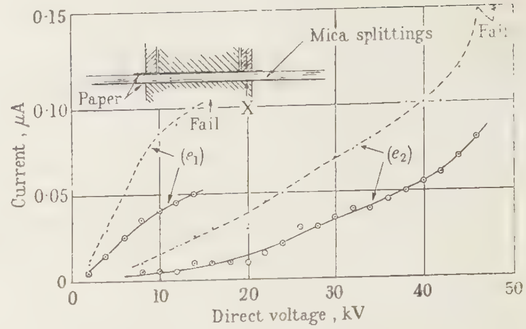


Fig. 12.—Specimens (e_1) and (e_2) consisting principally of loose mica splittings.

Thickness of layer of mica splittings (specimen e_1—20 mils; specimen e_2—30 mils).
——— Centre-electrode current.
— — — Total current.

presence of a defect been reliably indicated in the course of the current/voltage test, nor has a reasonable forecast of the breakdown voltage been possible. In general, precipitate breakdown has been the only real evidence of dielectric weakness.

(4.2) Defects leading to Surface Failure

The several specimens next tested contained artificial defects, usually in the form of complete perforations, displaced laterally from one or both of the test electrodes so as to introduce a surface-leakage path in the line of probable failure. Details of these specimens and results of the tests are given in Table 3. All tests were made in air at room temperature.

Failure in all cases resulted from flashover between the electrodes through one or more of the symmetrically positioned defects. With most specimens, currents typical of sound specimens were obtained, until unpredicted failure by flashover occurred. Intermittent sparking often preceded unmistakable flashover, the range of voltage over which this was experienced being implied in the recorded results.

In two cases only was a significant increase in current prior to flashover observed. The first was that of a sheet micafolium specimen (g_3), perforated at points 3 in from the upper measuring electrode. This specimen is illustrated and gave the results recorded in Fig. 13. Current measurements were unstable, but the approach of failure, although protracted, was unmistakable.

The second case was that of the micafolium-insulated metal tube (h_{1-2}) which gave the results plotted in Fig. 14. Three sets of measurements up to flashover voltage were made with effective distances between defect and surrounding band electrode of 1 in, 2 in and 4 in, respectively. This was repeated after removal of the outer wrapping of shellac-treated paper, which evidently was of a somewhat low resistivity. A fair estimate of failure, based on the initial bend in the curves obtained, would seem possible. Subsequent irregular behaviour at the higher voltages, which is associated with surface-leakage-discharge effects, complicates the interpretation of this part of the curve.

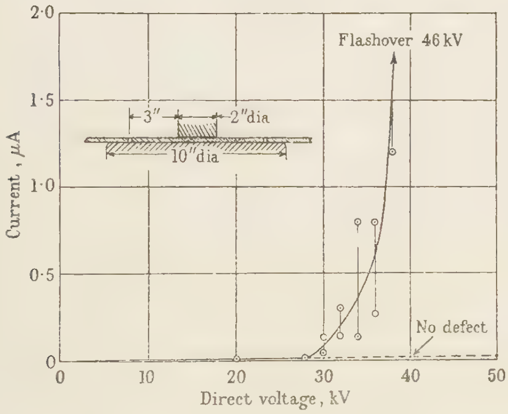
A marked change in behaviour was experienced when the outer wrapping of shellac-treated paper was removed to expose, mostly, a mica surface. Currents, at first of a very low order, increased abruptly at the critical voltage indicated, and exceeded eventually the 100 μA maximum of the meter. These high currents were quite stable, and no transient sparking was observed. Ultimate flashover occurred at from 8 to 16 kV above the critical voltages.

In general, the results of this group of experiments demonstrate the unreliability of the test, even for the prediction of surface failure. Where a distinct bend in the current/voltage curve occurred, the accuracy of a prediction based on this bend is

Table 3

Surface-Leakage Test Results on Artificially Defective Specimens

Specimen	Material	Defect	Breakdown voltage	Comments
			kV	
(f_1)	Micafolium board, 25 mils thick	Four $\frac{1}{8}$in holes spaced 90°, 1 in outside 2 in-diameter electrodes	36–40	Unpredictable flashover
(f_2)	Black varnished cloth, 28 mils thick	Four $\frac{1}{8}$in holes spaced 90°, 1 in outside 2 in-diameter electrodes	37–44	Unpredictable flashover
(g_1)	Micafolium board, 30 mils thick	Four $\frac{1}{8}$in holes backed by h.v. electrode, positioned 1 in outside measuring electrode (see Fig. 13)	22–24	Unpredictable flashover Maximum current, 0·02 μA
(g_2)	Black varnished cloth, 28 mils thick	Four $\frac{1}{8}$in holes backed by h.v. electrode, positioned 1 in outside measuring electrode (see Fig. 13)	25–27	Currents as for non-defective specimen, unpredictable flashover
(g_3)	Micafolium board, 30 mils thick	Four $\frac{1}{8}$in holes backed by h.v. electrode, positioned 3 in outside measuring electrode (as Fig. 13)	34–46	See Fig. 13; evidence of approaching flashover
(g_4)	Black varnished cloth, 28 mils thick	Four $\frac{1}{8}$in holes backed by h.v. electrode, positioned 3 in outside measuring electrode (as Fig. 13)	25–34	Currents as for non-defective specimen, unpredictable flashover
(h_1)	Micafolium wrapping, 0·1 in thick, on 1 in-diameter metal; shellac-paper surfacing	Four $\frac{1}{8}$in metal-paste-filled holes displaced 1 in, 2 in, and 4 in from outer tinfoil electrode (see Fig. 14)	1 in—27 2 in—43–45 4 in—62–65	See Fig. 14; bend in curve at about 80% of flashover voltage
(h_2)	As (h_1) but with shellac-paper removed to expose mica	Four $\frac{1}{8}$in metal-paste-filled holes displaced 1 in, 2 in, and 4 in from outer tinfoil electrode (see Fig. 14)	1 in—22 2 in—34 4 in—60	See Fig. 14; current increased to above 100 μA before flashover occurred



ig. 13.—Micafolium specimens (g_3) with holes external to 2in-diameter measuring electrode.

hown to depend upon the surface or near-surface conditions revailing.

(5) H.V. STATOR INSULATION

(5.1) Tests on Complete Stator

In parallel with the work on laboratory specimens of insulation, urrent/voltage tests at high potential were applied to the stator inding of an 11 kV synchronous motor which had been in rduous service for 15 years. The stator coils were insulated ith shellac micafolium on their slot portions, and with mica nd varnish cloth tapes on the end-windings. When first tested, ne windings were in a rather dirty condition—in particular, nsulation adjacent to the core at the bottom of the stator was eavily coated with dirt. The resistance of each phase to earth as 30 megohms.

The frame was placed on insulated blocks, and d.c. leakage ests were carried out with the frame excited positively, the indings being earthed through the measuring leads. This

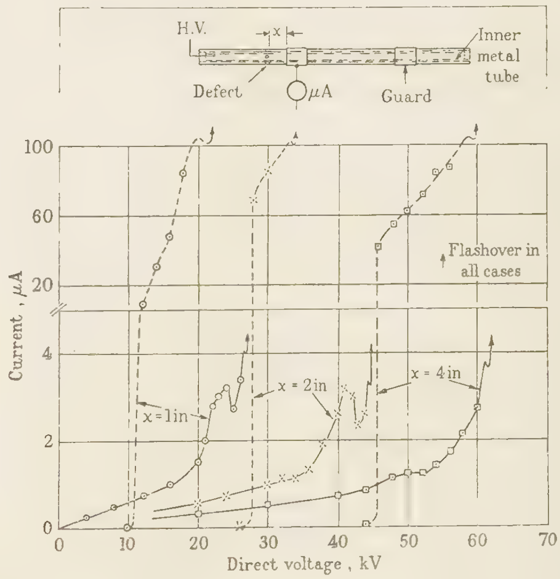


Fig. 14.—Surface-leakage test results on shellac-micafolium-wrapped metal tube [Specimens (h_1) and (h_2)].

——— Specimen (h_1)—Shellac-coated paper surface.
— — — Specimen (h_2)—Mica surface (shellac-coated paper removed).

arrangement, together with the use of jack plugs and sockets, enabled separate readings to be obtained on the three phases without discharging or reconnecting the machine.

(5.1.1) Direct-current/time Characteristic of One Phase.

In order to ascertain the time necessary to reach a steady current condition, the curves shown in Fig. 15 were measured on one phase at direct voltages of 5 and 10 kV, respectively. These show that changes occupy between 10 and 15 min, and so give some indication of the lengthy procedure in obtaining

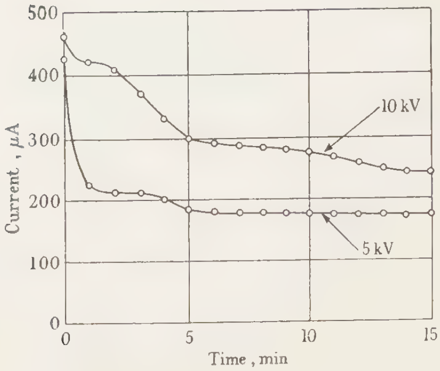


Fig. 15.—Current/time characteristic of phase A of 11 kV stator winding.

current/voltage curves. It seems evident that long-term changes of this order are due to lack of dielectric homogeneity and principally to the charging of capacitance through long surface and interlaminar resistive creepage paths.

Before taking further tests the insulation of the stator was dried, until its resistance rose to 500–1 000 megohms per phase.

(5.1.2) **Direct-current/voltage Tests.**

Current/voltage curves were then obtained on all three phases of the dried stator as shown in Fig. 16. In phase C, the current

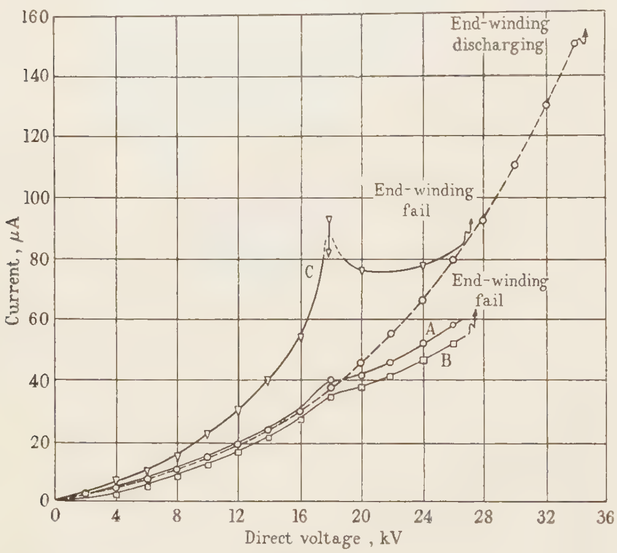


Fig. 16.—Current/voltage characteristic of 11 kV stator winding.
○ Phase A.
□ Phase B.
▽ Phase C.
— — — Further test, phase A.

was consistently higher than in the other phases, and at 18 kV some instability occurred accompanied by audible discharge in the end-windings. However, the current later became stable, and the voltage was further increased until at 28 kV phase C broke down. On retesting phases A and B, the latter was found to have failed also. Both failures were near, but outside, the end of a slot at points covered with dirt. The test was continued on phase A and gave the chain-dotted curve in Fig. 16. At 34 kV violent discharges occurred around the end-windings, and the test was discontinued. Faulty coils were isolated and connected to the frame, and the healthy remainder of phases A and C were retested as shown in Fig. 17. Although there was instability

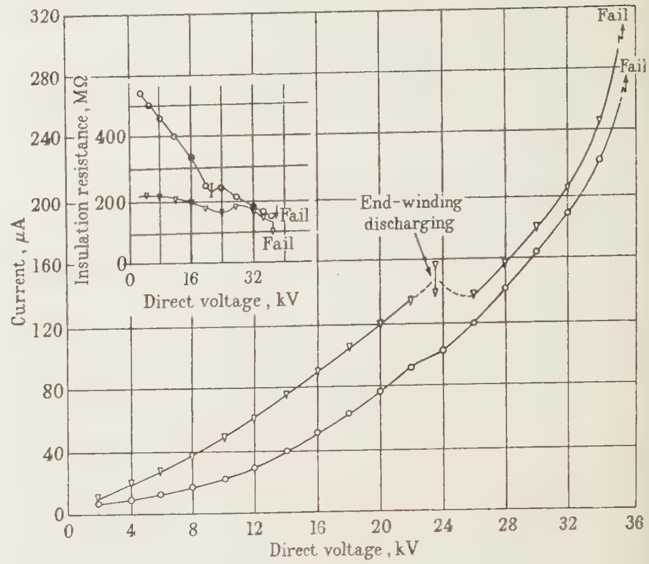


Fig. 17.—Current/voltage and insulation-resistance/voltage characteristics of healthy parts of 11 kV stator winding.
○ Healthy part, phase A.
▽ Healthy part, phase C.

in phase C at 22 kV, the test was continued to 36 kV before failure occurred almost simultaneously in both phases. Both failures were in the end-winding adjacent to the core.

The corresponding insulation-resistance/voltage curves are shown for comparison plotted as an inset in Fig. 17, and as a means of predicting breakdown they do not appear to have any advantage over the current/voltage curves.

(5.1.3) **A.C. 50 c/s Rapid-breakdown Tests on Remaining Healthy Parts of Phases.**

To estimate the a.c. strength of the winding, all faulty coil groups, which now amounted to some 30% of the winding, were connected to the frame and earthed, and the exposed ends of the healthy part of the winding were insulated from earthed parts with micanite sheets. When the voltage was raised to 16 kV (r.m.s.) visible discharges appeared at several places on the end-windings, adjacent to the core. At 26 kV, flashover took place to the cut ends of some faulty coil groups, but a true breakdown did not occur.

(5.1.4) **Comments**

All direct-current/voltage tests carried out on the stator resulted in end-winding breakdowns and did so without any obvious prediction of failure. The dirty condition of the end-windings influenced the tests, and intermittent current instability was encountered. Such effects are associated with surface leakage and with transient charging currents as the stress redistributes itself following partial surface breakdowns in the end-windings. Whereas all failures experienced in these tests occurred in the end-windings, service experience shows that the greater part of all stator-winding failures originate as turn-to-turn faults in the slots.[10]

(5.2) **Tests on Individual Coils from Stator**

Because of the inconclusive nature of d.c. measurements on the stator, further tests were carried out in the laboratory on coils taken from various parts of the winding; some of these had been in service near the line end and showed unmistakable deterioration from corona, while others which had served at a lower voltage retained almost their original condition.

Before applying direct current, alternating power-factor/voltage ests were made. Both a.c. and d.c. tests employed a centre infoil electrode 12in long with a 2in guard on each side, all hree tightly wrapped and applied with petroleum jelly centrally o the slot portions of the coil sides.

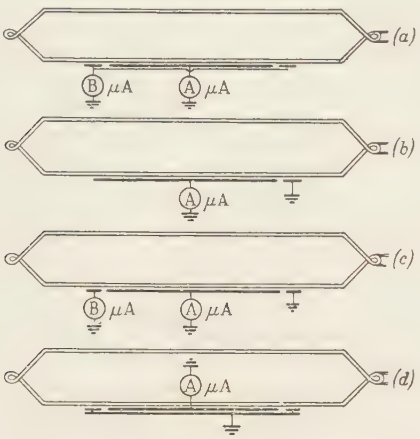


Fig. 18.—Electrode arrangements.

(*a*) Unguarded (A + B), guarded (A) from both end-windings.
(*b*) Unguarded from non-connection end-winding.
(*c*) Unguarded (A + B), guarded (A) from non-connection end-winding.
(*d*) Guarded from both end-windings and screened.

For the d.c. tests the arrangement shown in Fig. 18(*a*) enabled he centre-electrode current at A to be measured either separately or together with the guard current at B.

5.2.1) A.C. Loss-tangent/voltage Tests.

Examples of the curves obtained are shown in Fig. 19. The oss-tangent/voltage tests clearly distinguish between the corona-eroded coils E_1, E_2, with 15 years' service at the h.v. end, and oils of similar type N_1, N_2, from the neutral end.

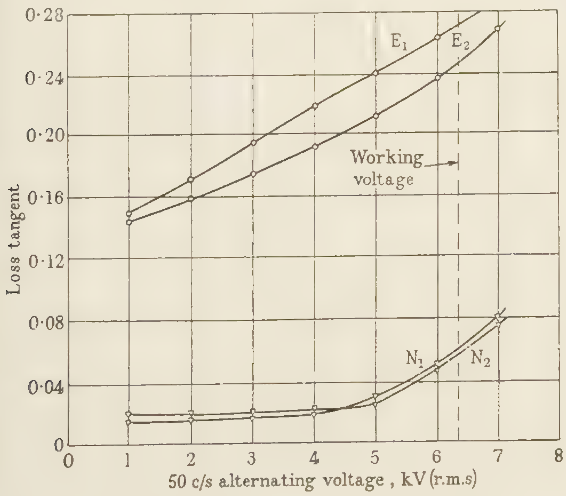


Fig. 19.—Loss-tangent/voltage characteristics of 11kV stator coils.

E—Eroded coils with 15 years' h.v. service.
N—Coils from the neutral end.

.2.2) Direct-current/voltage Tests.

Using coils of known a.c. loss tangent, direct-current/voltage neasurements were carried out both with slot portions unguarded nd guarded as in Fig. 18(*a*); Figs. 20 and 21 are the respective

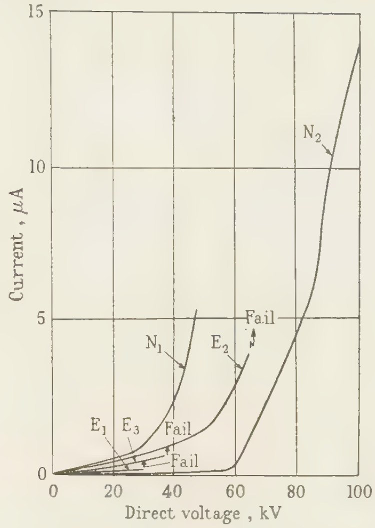


Fig. 20.—Current/voltage characteristics of 11kV stator coils—unguarded [Fig. 18(*a*)].

E—Eroded coils with 15 years' h.v. service.
N—Coils from the neutral end.

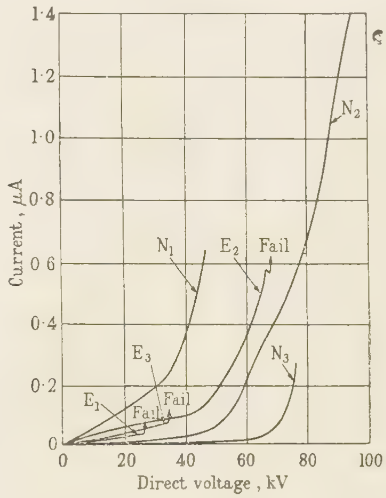


Fig. 21.—Current/voltage characteristics of 11kV stator coils—guarded [Fig. 18(*a*)].

E—Eroded coils with 15 years' h.v. service.
N—Coils from the neutral end.

curves, and show the points of failure. It is clear that a higher order of current is obtained when the electrode is not guarded, but apart from this, the tests fail either to predict a coming breakdown or, except by actual failure, to distinguish between badly eroded coils, E, and others, N, in sound condition.

The high currents prevalent in the unguarded condition show that leakage currents from the end-windings could overwhelmingly influence the results obtained when testing a stator; they certainly would override such apparent predictions of failure as of N_3 in Fig. 21.

(6) DEPENDENCE OF D.C. LEAKAGE CURRENT ON VARIOUS FACTORS

It was clear by now that factors contributing to the direct current measured at the higher voltages included discharge effects in the end-windings and perhaps extraneous corona.

Precautions were therefore taken to reduce such corona by using connections of substantial diameter and applying insulating compound to surfaces subjected to high stress.

The following factors were then examined:

(a) Dirt on end-windings,
(b) Guarding,
(c) External corona,
(d) End-winding fault,
(e) Different types of h.v. coil insulation.

To do this and to represent more closely the actual slot, the electrode systems differed from those used previously in that the centre electrode now covered the total core length of the coil side, 1 in guards being used when required. These arrangements are shown in Figs. 18(*b*)–18(*d*).

The complete screening of Fig. 18(*d*) was achieved by wrapping a thin polythene sheet round the electrodes and then applying an earthed tinfoil sheath.

(6.1) Dirt on the End-windings

The windings of a machine in service accumulate dirt. The effect of this is demonstrated in Fig. 22, which shows two curves

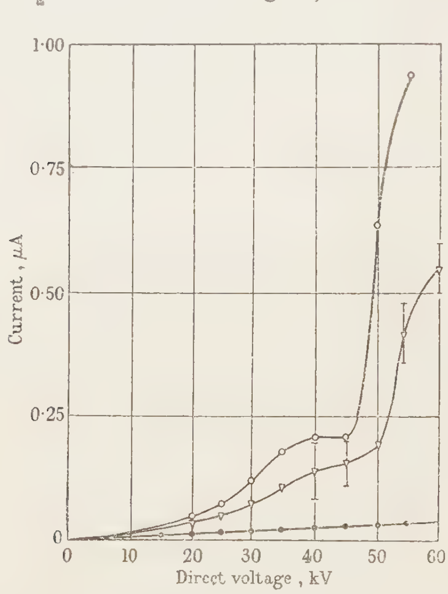


Fig. 22.—Effects of dirty end-windings and guarding of an 11 kV stator coil on the current/voltage characteristic.

○ Shellac-micafolium coil—partly guarded [Fig. 18(*b*)], end-windings dirty.
▽ Same coil—partly guarded [Fig. 18(*b*)], end-windings clean.
-•- Same coil—fully guarded [Fig. 18(*c*)].

obtained on a shellac-micafolium coil from the neutral end, tested with the non-connection end unguarded using the electrode arrangement of Fig. 18(*b*), the top curve before cleaning and the middle one after cleaning. The latter shows the instability of leakage and discharge currents above 40 kV (indicated by the vertical lines) associated with the end-windings. This phenomenon of end-winding charge and discharge was frequently encountered when testing dry aged insulation, and is not to be confused with an effect due to steady corona discharge discussed in Section 6.3.

(6.2) Effect of Guarding

The tests on this and other coils indicated that the currents measured were appreciably influenced by the condition of the end-winding insulation. Consequently the coil was retested again, guarding the non-connection end as well, using the electrode arrangement shown in Fig. 18(*c*). The bottom curve of Fig. 22 was then obtained and shows the marked effect of guarding, the true slot-insulation current being quite small and increasing linearly with voltage over the test range.

(6.3) Effect of External Corona

To explore the effect of external corona, tests were taken on an 11 kV coil with micafolium in sound condition, first with the non-connection end unguarded as in Fig. 18(*b*), and then fully guarded as in Fig. 18(*c*). The results obtained are shown in Fig. 23. The curve for the former test condition is of interest in that a maximum occurred at approximately 58 kV. This phenomenon was also observed in earlier tests on specimens and on the complete stator. Observation suggests that such maxima are accompanied by a readjustment of stress in the end-windings such as might occur by the breakdown of small air-gaps between tapings.

The curve obtained for the guarded condition shows a sharp rise just above 80 kV, giving a very plausible prediction of failure, but it was suspected that an audible discharge arising from the test equipment was associated with this result. The test was therefore repeated, this time with the guarded slot portion completely screened [Fig. 18(*d*)]. The result as shown in Fig. 23 was to eliminate completely the upward bend in the curve.

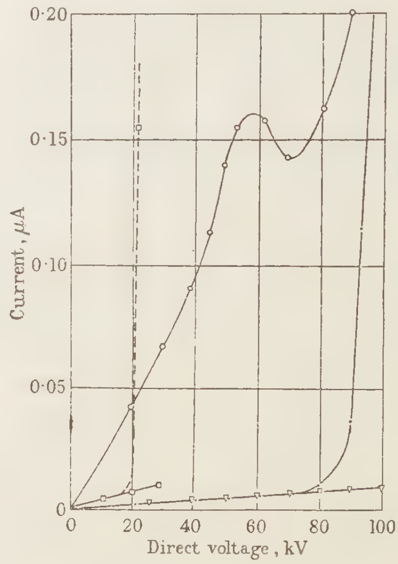


Fig. 23.—Effect of external corona on stator coil current/voltage characteristic.

○ 11 kV coil unguarded at non-connection end [Fig. 18(*b*)].
-•- 11 kV coil guarded [Fig. 18(*c*)].
▽ 11 kV coil screened [Fig. 18(*d*)].
□ 3 kV coil guarded [Fig. 18(*c*)].
— — — 3 kV coil with external corona.

A similar test was carried out on a 3 kV coil to determine the current/voltage curve on the slot portion in the guarded condition. The test was repeated, but this time introducing at 20 kV an independent external source of d.c. corona. The curves obtained, also shown in Fig. 23, confirm the marked influence which external corona can have, as indicated by the dotted curve, on the current/voltage form.

(6.4) Effect of an End-winding Fault

The influence of an end-winding fault on the current/voltage characteristic was noted using two 3 kV coils fully guarded [Fig. 18(*c*)], one insulated with bitumen-impregnated mica tape and the other with shellac-micafolium.

Both coils had previously suffered end-winding puncture adjacent to the straight portion not undergoing test, so that the puncture was quite remote from the healthy side; nevertheless, occasionally, erratic behaviour of the healthy side was experienced, heralded by audible and visible discharge from the remote fault. Current/voltage characteristics are shown in Fig. 24, where the dotted lines indicate the occasional discharge.

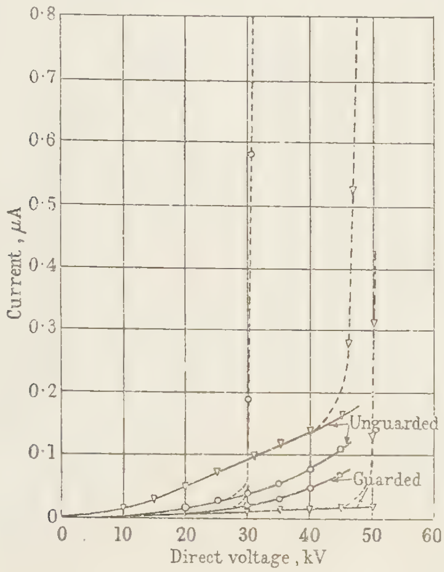


Fig. 24.—Effect of end-winding fault on 3kV stator coil current/voltage characteristics.

○ Bitumen-impregnated mica-taped coil.
▽ Shellac-micafolium coil.
— — — With remote end-winding fault discharging.

(6.5) Comparison between Coils of Different Types

The current/voltage characteristics of three types of stator coil were determined, using (*a*) two 11-kV shellac-micafolium-wrapped coils with taped end-windings, one a spare and the other in sound condition taken from the stator returned from service, (*b*) a 3kV bitumen-impregnated mica taped coil, and (*c*) two new 11kV bitumen-micafolium wrapped coils with taped end-windings. The curves were obtained with a partly guarded electrode arrangement [Fig. 18(*b*)]. As shown in Fig. 25, the bitumen-micafolium coils gave characteristics which rose somewhat at voltages above 40–50kV. Where end-winding discharges contributed to current variation, this is indicated by a thick vertical line joining two points. Curves for the shellac-micafolium coils rose earlier and more steeply. The abrupt increase of current at the higher voltages is attributed to leakage and discharge from the unguarded end-winding and reflects the degree of end-winding consolidation. The curve for the 3kV bitumen-impregnated mica-taped coil was linear up to the point of failure.

(6.6) Comments on Factors influencing the D.C. Leakage Current

Dirt on the end-windings has some influence upon the current/voltage curve, but clean surfaces on coils which have undergone service can lead to intermittent charge-discharge effects.

The effect of guarding is marked, for when coils in the unguarded condition are tested, the greater part of the current measured frequently comes from distant parts of the end-winding. Moreover, any external corona discharge in the vicinity of the test, whether from the end-winding or external to it, can contribute materially to the characteristic obtained and may dominate it.

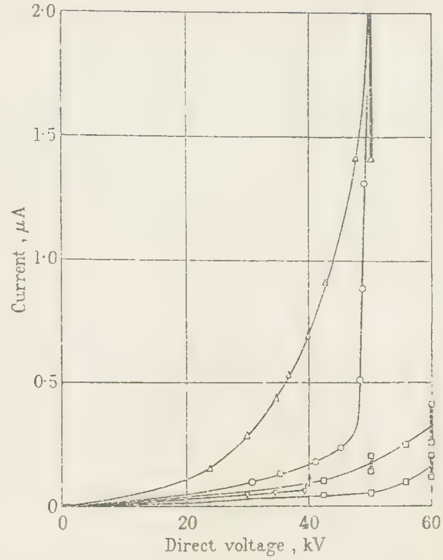


Fig. 25.—Current/voltage characteristics of various h.v. stator coils—unguarded [Fig. 18(*b*)].

○ 11kV shellac-micafolium coil after 15 years' service at the neutral end.
△ 11kV shellac-micafolium spare coil.
□ 11kV bitumen-micafolium coils.
▽ 3kV mica-taped bitumen-impregnated coil.

(7) CONCLUSIONS

Non-destructive tests with high-voltage direct current fail to distinguish between good and deliberately faulty specimens of insulation. Both give smoothly-rising current/voltage curves free from any feature by which a breakdown value can be reliably assessed. Only when surface discharge is involved in the breakdown process—as in the surface-leakage form of test—is a prediction of failure possible, and in such cases the failure so predicted is essentially that of the air path.

Tests of this nature, whether applied to a complete high-voltage stator winding or to single coils, can lead to no real judgment of the electric strength of the slot insulation. Whenever a sudden increase of current, suggestive of approaching failure, is obtained in such tests it is derived principally from discharge and leakage effects in the end-winding, which differ so materially from those under a.c. conditions as to render the results irrelevant to an a.c. machine in service.

(8) ACKNOWLEDGMENTS

The authors are indebted to Dr. K. J. R. Wilkinson for much helpful advice; they also wish to thank Mr. L. J. Davies, Director of Research of the British Thomson-Houston Co., Ltd., for permission to publish the paper.

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DISCUSSION BEFORE THE SUPPLY SECTION, 16TH MARCH, 1955

Mr. E. Jones: The authors are to be congratulated on the very careful work they have done to assess high-voltage d.c. testing, especially in view of the large volume of published work in the United States and Canada, which in the main seems to advocate the use of direct current.

The authors comment that the evidence presented by Moses[8] "shows that the amount of deterioration likely from normal alternating over-potential tests curtails the life of a winding by an altogether negligible amount. . . ." I would entirely agree with this, although it is, of course, true only in the case of well-made insulation. It seems to me that the d.c. test will be less stringent than the a.c. test if the insulation is not well made, or if the insulation contains materials which are susceptible to attack by discharges. Therefore, a d.c. test may possibly pass insulation which is inferior for use in a.c. windings.

Reference might be made to the insulation developed some years ago in the United States for large stator coils, which consists of mica insulation impregnated with, for example, polyester resin. It is conceivable that the impregnant is to a degree susceptible to internal discharges; furthermore, the percentage of impregnant in the insulation may be somewhat on the high side. Therefore d.c. testing in this case may well be less harmful than a.c. testing. In other words, d.c. testing might give a false sense of security.

A similar argument could be used regarding coil insulation of integrated mica. The percentage of impregnant or bond is much greater than with mica-splitting insulation, and here again d.c. testing may give an entirely false sense of security.

I entirely agree with the authors' finding that the insulation-resistance/direct-voltage characteristics do not predict the failure of a winding. The company with which I am associated has done tests on several new windings and several old ones. In no case was there any sign of prediction of failure.

In the testing of windings we have had many cases of what might be called strong pseudo-prediction, or prediction in accordance with the line of reasoning used by Cameron[5] in his paper some years ago, but on reaching the direct voltage where failure is expected, the insulation-resistance/direct-voltage characteristic takes a turn for the better and becomes asymptotic to the base line. It is possible in many cases to increase the direct voltage to an incredibly high value, still without failure, although according to Cameron's reasoning there should have been failure at a much lower voltage. In other words, it is not possible to decide what is a genuine prediction. The prediction can be proved only by obtaining a failure, and therefore I suggest that it is not a prediction at all.

It is unfortunate that the determination of the loss-angle/voltage characteristic of a large winding is so tedious and that such a large h.v. transformer is needed, as this test seems to give a good comparative idea of the deterioration of any of the coils due to ionization, which is shown in Fig. 19. Admittedly, it is difficult to know where to draw the line beyond which one should not continue to operate a machine, but experience should eventually enable limits to be set.

The observation of discharges, using equipment such as the E.R.A. discharge detector, would be an interesting line to follow, although to develop the necessary experience with the equipment would take a considerable time. Such a test would be based on a much sounder foundation than the insulation-resistance/direct-voltage characteristic.

This discharge detector on its own, however, would not be sufficient. It would be essential to carry out a high-voltage test to find any cracks in the insulation due to electro-mechanical disturbances or mechanically-applied damage. For such a high-voltage test, direct current would be preferred, owing to the simplicity of the test equipment and the reduced damage to insulation, as compared with high-voltage alternating current.

In many cases the Americans use a thickness of insulation on the overhangs which is the same as that on the slot portion. The overhangs are sometimes covered with resistance grading, and this may affect the results somewhat. What are the authors' views on this point?

Mr. A. W. Stannett: In 1952–53, 22 stator faults were recorded by the B.E.A. This number is far too great, and some kind of test is needed so that potential failure can be detected at an early stage.

The authors have made a valuable, although negative, contribution to the subject in showing that the breakdown strength of stator insulation containing artificial voids cannot be predicted reliably by insulation-resistance tests over a range of voltage. However, much more information is required before insulation-resistance tests are rejected. For example, the authors have given the current/voltage characteristics of insulation containing artificial voids, but probably different characteristics would be obtained on the same samples after the voids had been discharging for a year or so, as under service conditions. Breakdown due to discharge in voids is a slow process usually affecting the insulation resistance of the neighbouring material, and it might well be possible to estimate the amount of deterioration by regular tests.

In spite of their known limitations, insulation-resistance tests are of some assistance in determining the general condition of a machine insulation, and we are endeavouring to obtain more data on machines in service. The results available at present suggest that a modern machine has an insulation resistance of the order of 2000 megohms, and this is sensibly constant up to a direct test voltage equal to the r.m.s. working voltage. The current takes at least 15–20 min to reach a steady value. Very old and possibly damp machines have an insulation resistance of the order of 10–50 megohms. In such cases, the insulation resistance usually reaches a final value in two or three minutes. Abnormal results have been recorded where the insulation resistance appears to decrease with time of application of voltage. Here, it is sometimes found that the insulation resistance decreases at each voltage change, whether the voltage is raised, lowered or merely switched off after earthing the stator for a time, and switched on again. Results such as these support the authors' contention that dirt and moisture materially affect the

results. They prompt me to ask, however, whether the curves in Fig. 15 were modified by drying and also whether or not those in Figs. 16 and 17 were repeatable, since one would expect the insulation resistance of part of a winding to be greater than that of the whole.

It would be helpful in assessing results and in developing tests to have more information concerning the mechanisms of the commonest types of service breakdown.

Mr. D. Smith: I have recently applied the d.c. over-potential test to two alternators. In one case the d.c. resistance decreased noticeably at high voltage and in the other case it did not decrease. When subsequently stressed to breakdown by an a.c. over-potential test, the former broke down in the end-winding at a peak voltage which was very approximately the "predicted" value. The second alternator broke down in the slot section at a voltage which could not have been predicted. This is precisely the behaviour the authors would have expected from their analysis.

One common feature of the two resistance characteristics was an increase in resistance with increasing voltage at low voltages. The effect is not mentioned by the authors, but it is referred to by Cameron in the discussion on Reference 7. It can be discerned in some of the authors' results and is of importance since it represents a phenomenon which is opposed, in effect, to the one under discussion.

The widespread interest in this test and the number of alternatives which have been proposed (e.g. polarization index, specific absorption, dispersion, etc.) emphasize the demand for a more satisfactory test than the low-voltage d.c.-resistance test. In exposing the severe limitations of the d.c. over-potential test the authors have enabled the search to concentrate on other methods. In this respect Fig. 19 appears encouraging, although the procedure involved in high-voltage power-factor testing is a problem in itself.

The E.R.A. discharge detector which measures the energy dissipated by individual discharges was used in conjunction with the alternator tests mentioned above. Although the two alternators, which were 11 kV machines, behaved quite differently, one breaking down in the overhang (at 28 kV) and the other in the slot (at 22 kV), the discharge characteristic was very similar for the two machines. The discharge detector remained connected during the a.c. breakdown test on the machine which failed in the slot section. No significant change in the observed characteristic was obtained as breakdown was approached. This was disappointing, but it is possible that aspects of the discharge characteristic other than those at present measurable with this type of detector may reveal the state of the insulation in a more satisfactory manner. Finally, the authors appear to have been so thorough in their condemnation of the direct-current/voltage measurement as a test for alternator insulation that they may have inadvertently cast a cloud over d.c. testing in general. I am sure they would agree that, in cases where the a.c. and d.c. field distributions are similar, the d.c. withstand test is a useful one.

Mr. F. S. Edwards: The authors state quite positively that the high-voltage d.c. method of testing has no valid basis as a means of assessing the serviceability of the insulation of stator coils. Almost the whole support for the opposite view is found in the paper by Cameron,[5] one notable feature of whose tests is that the four machines which he examined were all water-wheel alternators, and moreover were 27–45 years old; two of them were low-voltage machines wound for 2·3 kV, and two of them were wound for 6·6 kV.

If all the bars are in the same condition (either good or bad) then clearly we can at least measure their characteristics. However, Fig. 19 shows that the bars are most unlikely all to be in the same condition. In this Figure the coils close to the neutral have a power factor of 0·02–0·04, and those close to the line end have a power factor of 0·13–0·25. Figs. 20 and 21 show that the direct breakdown voltages of the two groups of coils are quite different. Unfortunately, however, a power-factor measurement on a complete phase will give only the average of all the bars in that phase, and it will be necessary to break the windings into small sections in order to obtain figures—which are nevertheless still averages—for the various sections. Also, Fig. 20 shows substantial variations in the breakdown voltages of individual coils, both taken from the line end, so that even if the bars could be measured singly or in small groups there would still be considerable uncertainty in the test.

Where then can we find the selective test that we want, remembering that a defect ultimately leading to a breakdown may well be confined to a small part of one bar?

In addition to locating, or at least indicating, the presence of such a defect, the ideal method should also preferably meet two other requirements.

(i) It should be capable of being applied without the removal of the rotor.

(ii) If possible, it should be capable of being applied without shutting down the machine.

The d.c. and a.c. tests already discussed will show up widespread deterioration, and hence if the results are bad the insulation may safely be condemned. Unfortunately, however, it is not safe to assume that all is well if the results are good.

I can only see one way (as yet untried, so far as I know) which holds out hopes of success and of discrimination between local and general deterioration. From the frequency with which references are made in the American technical press to "slot discharges" it is reasonable to suppose that some of the failures abroad are caused by, or at least preceded by, this phenomenon.

A suggestion has been made that we should attempt to monitor the discharge while the machine is running.

The best place to measure would probably be across small inductances in the three leads to the neutral point. A cathode-ray oscillograph could be used for monitoring, and once fitted, the equipment could be left connected and switched on at intervals for the examination of the trace on the screen. Whatever the effect of the ordinary corona discharge on the trace, it is possible that the marked development of slot discharge on even one bar would make a significant alteration to the trace and would constitute a warning to the operating staff. How effective such a method would be cannot be determined without experiment, but obviously a virtually continuous recording process, involving no interference with the ordinary running of the station, has everything to recommend it, if only—to quote the authors—"we can be certain that it can really achieve its object." I hope that a trial will be carried out.

Mr. L. D. Anscombe: The authors' investigations arose from a proposal made by an associated machine-design group that high-voltage d.c. testing should not only be recommended to users as a means of assessing the condition of stator insulation after years of service but also used for quality control in the manufacture of coils. At that time we had been led by optimistic reports from the United States to believe that this might be the ideal test in either case.

As the work proceeded, however, it became clear that there were grave defects in the method, and these adverse results are now beginning to be confirmed by other American investigators. Although this is a disappointing outcome, we should be much indebted to the authors for the painstaking and authoritative way in which they have tackled the problem and explained many of the anomalies encountered in this type of test.

It seems that the main disadvantage of high-voltage d.c. testing lies in the fact that it fails to detect defects in the slot portion of coils which are likely to lead to trouble in service, but may seek out what might almost be described as spurious weaknesses in the end-windings. The potential distribution under a.c. test, as under service conditions, is determined by capacitance, and modern coils have corona shields which are graded at the ends of the core, in order to control the voltage gradient at this point. In a d.c. test, the voltage distribution over the end-windings is controlled entirely by the resistance of leakage paths in series with the corona shields, and it can lead to breakdowns far out in the end-windings. This is a type of breakdown which does not normally occur either on high-voltage a.c. tests or in service. It would thus appear that there is some danger that, in applying very high direct voltages to machines that have seen many years of service, a spurious breakdown of this kind may occur.

Very little attention seems to have been paid to the subject in this country, and it may be that our experience with high-voltage a.c. windings has been more favourable than in other countries. There is, however, a need for a reliable service test for the condition of insulation in old machines. Although the tan δ test would give the required information, it is too difficult to carry out on installed plant. I have recently seen interesting results obtained by French investigators using the method of measuring the absorption current obtained on discharging the winding following the application of low-voltage direct current. This current, after a fixed interval of time in relation to the capacitance of the winding, appears to give a good indication of the extent of deterioration. I should be interested to have the authors' views on the value of such a test.

Mr. L. W. James: The authors' conclusions are somewhat disappointing, since, with a view to obtaining a useful test for turbo-generators, we have been following the American and Canadian publications, dealing with non-destructive d.c. testing, very closely, and these appeared to indicate that very satisfactory results had been obtained over the last five years.

Routine over-voltage testing has not been standard practice in this country, and in general, operating engineers are against over-stressing machine windings unnecessarily. The need for some such test on turbo-generators does not seem to be so definite as with the hydro-electric sets referred to in Reference 10, in which it is stated that many of the machines have to be rewound after about 11 years' service, which seems very serious. Admittedly, we are dealing with different types of machine—the hydro-electric machine as against the turbo-generator.

So far as turbo-generators are concerned, on the system in this country over the last six or seven years, dealing with stator-insulation failures only, we have had an annual rate of breakdown of the order of 1% of the total number of sets installed. Whilst any failure in service is serious, the position does not appear to demand any immediate change in the normal routine maintenance practice (which, I understand, generally consists in a test with an insulation tester at a relatively low voltage) unless some very definite evidence of the usefulness of a new method of testing is forthcoming.

In general, with a slot failure on a turbo-generator, the fault does relatively little damage apart from that done to the faulty coil, provided that the protective gear operates satisfactorily and trips the machine out quickly. With end-winding faults the damage is often much more serious, owing to the initial arcing setting fire to the end-winding insulation, and we are then faced with a more serious problem in repairing the machine. Therefore if d.c. testing shows up weaknesses in end-windings, it might be worth while adopting for that reason alone.

In connection with a.c. testing it is stated that the amount of deterioration likely from normal alternating over-potential tests curtails the life of the windings by an altogether negligible amount, although there have been many statements to the contrary. Certainly it does appear that deterioration has occurred when we repeat a high-voltage test and occasionally get failures at voltages below the previous test voltage, although the two tests may have been carried out in a period of a day or so and no obvious damage has occurred to the windings in between the two tests. This may be purely a case of random variations of test voltage, test equipment, or atmospheric conditions, but it would be useful if we could have some definite evidence to show that repeated a.c. over-potential testing at reasonable voltages does not cause any deterioration of the insulation.

Mr. T. H. Milne: The leading question posed by the authors is why the Americans should obtain comparatively positive results in this field whilst the conclusions reached by the authors are so completely the reverse. One must assume that the Americans would have as little use for a futile technique as we would. It is true that they did not succeed in forecasting breakdown in every case, but the paper suggests that they could not have done so in any circumstances. Is the answer to be found in different methods of construction, or the age of the insulation tested, or the materials involved, or is it rather in the technique adopted, the interpretation of results or the preponderance of hydro-electric plant in the tests?

Some time ago the North Eastern Division of the C.E.A. took an interest in the Americans' claims, and quite recently have conducted some tests on a 6 MW 5·2 kV turbo-alternator at Sunderland power station. The machine was built in about 1917, and after operating for 30 years has laid idle for about 7 years. Nothing was done to clean the windings, which were in a very dirty condition. From the outset we were not primarily concerned with the desirability of forecasting breakdown but rather with the development of a technique that will detect flaws in the insulation, using probes or by other means not necessarily employing very high voltages. It is felt that there is room for such a technique to provide more knowledge than can be gleaned from a visual examination and voltage test and from considerations of the age and history of the insulation.

In the first place, a probe was used in conjunction with a filter, amplifier and headphones, and with each phase energized in turn at normal voltage, several spots were located and marked where an audible signal was discerned. This test was followed by energizing the windings at 2 kV d.c., and current was picked up from the surfaces of the end-winding insulation. Largely owing to the dirty state of the windings there was no difficulty in doing this, and it was noticeable that a considerable increase in current was obtained from the spots already detected by the probe.

These tests were followed by a high-voltage d.c. test to breakdown, each phase being tested in turn. The arrangement used was that the two unenergized phases were earthed via one microammeter, whilst the frame of the machine was earthed via a similar instrument. In two of the phases, most of the current was returned by the frame meter, one phase breaking down at 21 kV accompanied by an increase in the frame meter indication, probably a breakdown in a slot, whilst in the other case at 26 kV the meter in the phases climbed steadily until smoke emerged from the end-windings. In neither case was there any warning of breakdown, and readings at each incremental voltage step were quite steady. The third phase exhibited different behaviour inasmuch as most of the current was returned by the meter in the phases, which increased in a manner suggesting that breakdown was predictable. At 22 kV, however, another and unheralded breakdown occurred from a spark discharge to the frame accompanied by a rise in the frame-meter current. The plot of the insulation resistances for the three phases, based on

the total current in each case, confirms the authors' conclusions that the shape of the curves gives no warning of breakdown.

Fig. 22 indicates that only a minute current passed radially through the insulation in the slot portion of the coil, and the authors attribute the very large currents measured in the unguarded condition to leakage over the surface from the remote ends. Did the authors ascertain whether there were flaws in any part of this insulation which might have contributed locally to this large current?

One quality of new insulation is uniformity, and the bugbear of old insulation is the undetected weak spot. Three out of six breakdowns of stators with which I have been associated in recent years were of this type. Failure in service in each case could have been avoided if these flaws had been detected and repairs effected in time.

Mr. W. J. Carfrae: About 20 years ago we did some work on high-voltage d.c. testing in connection with some 62 500 kVA, 1 500 r.p.m., 33 kV alternators. We were then concerned about the large apparent-power load demanded by a.c. tests on high-voltage alternators, and the reduction in apparent-power demand by the use of direct current justified investigation.

A complete equipment was manufactured incorporating 100 kV rectifying valves with suitably insulated filament transformers, etc., and a series of comparative tests were undertaken. We concluded that d.c. tests were of no value in picking out latent faults in insulation. The stator bars in question were required to withstand 67 kV for one minute, and cases were encountered where a faulty bar withstood successfully 100 kV d.c. for one minute and on a subsequent a.c. test broke down at around 30–40 kV (r.m.s.). We were also concerned about the hazards arising from the excessive time taken for bars to become fully discharged on the conclusion of d.c. tests.

I am not altogether in agreement with the authors that the effect of high-voltage a.c. testing on the life of insulation is negligible. This is probably true for machines of the 6·6 or 11 kV class, but I am inclined to the belief that the standard twice rated voltage plus 1 kV a.c. test becomes increasingly severe in the high-voltage ranges, and that excessive voltage testing of high-voltage apparatus should be avoided as far as practicable.

I think that high-voltage d.c. testing may have a limited field of application in the detection of gross mechanical damage to insulation on a machine, e.g. during overhaul. The equipment is more compact and easily handled and the advantage is merely one of convenience.

I feel, however, that only alternating voltage and/or power-factor tests are of value in proving the quality of insulation by a single test. A series of d.c. leakage-current tests or tests with an insulation tester, taken at regular periodic intervals under carefully noted conditions of temperature and humidity, may afford some indication of the state of machine insulation, but the results must be interpreted with a good deal of caution and certainly could not form a basis for prediction.

(The authors' reply to the above discussion will be found on page 580.)

RUGBY SUB-CENTRE, AT RUGBY, 2ND FEBRUARY, 1955

Mr. K. W. McBain: No mention has been made by the authors of the percentage of ripple present in the d.c. supply, and I would be interested to know how good the smoothing was.

One of the disadvantages of the method used seems to be the tedious operation of obtaining and plotting the co-ordinates. It might be worth investigating whether a slowly rising pulse would not give a better criterion for predicting the ultimate breakdown voltage.

A further proposition is that measurement of current during d.c. tests carried out regularly at the same voltage would, if plotted against time, indicate any tendency towards premature ageing of the insulation as a whole. This proposition does not seem to have been examined by the authors, and their comments would be welcomed.

Mr. A. J. Ellison: Some of the biggest dislocations of industrial processes are caused by the unexpected breakdown of electrical machinery, and the means to forecast breakdown and carry out the necessary maintenance at a convenient time would be of great value. Some recent American papers gave the impression that the means was at hand, and that an insulation-resistance/voltage curve could be plotted for a machine, extrapolated to zero insulation resistance and the alternating breakdown voltage found in the direct-voltage result by the use of a simple ratio, all without damage to the machine. Later papers cast doubt on the validity of the method.

The authors have shown that this simple prediction is not possible for electrical machines or artificial assemblies of insulating materials, such as might be found in sound or faulty machines. They demonstrate how curves approaching a definite point in the way described may be produced using sheets of insulation between spring clips, the curves varying slightly with the surface condition of the insulation and remaining practically the same if the insulation is removed altogether.

One difficulty with all present high-voltage tests of machines, and which is particularly evident with high-voltage d.c. tests, is their artificial nature. It would appear that the ideal high-voltage test of an electrical machine is one in which the voltage distribution is normal but the voltage magnitudes are elevated. In high-voltage a.c. tests all parts of the windings are raised to the same voltage, and parts which can never experience high voltage in normal operation are put into a state when they may break down, despite the fact that they may be perfectly suited to their duty. In high-voltage d.c. tests conditions are even more artificial in that, because of the distribution of the insulation resistance and capacitance, the end-winding insulation is relatively more highly stressed than the slot insulation. There is thus an even greater danger with direct current of breaking down insulation which is perfectly satisfactory for normal service. I have experience of several cases where this has occurred.

The authors state that repeated high-voltage a.c. tests do not appear to weaken the insulation appreciably. Sidway and Connor* maintain the opposite. A steady a.c. high-voltage test may be regarded as a repeated impulse test, and Sidway and Connor conclude that repeated application of an impulse voltage less than that required for immediate breakdown will eventually produce failure.

I hope that work on the state of machines in service will continue. Investigations carried out jointly by users and manufacturers might produce valuable results. In what direction do the authors consider that such further work should proceed? Should the insulation loss angle be measured periodically? Should the deterioration of internal insulation be followed with a corona detector, applied locally along the slots? Or should studies with high-voltage direct current, perhaps considering particularly absorption currents, continue?

A very large Canadian user of high-voltage machines states that he has for several years had great success with high-voltage d.c. maintenance testing. This is difficult to understand in view of the apparently conclusive evidence of the paper. Would the authors comment on this?

* SIDWAY, C. L., and CONNOR, I. E.: "Effect of Overvoltages and Surges on Machine Insulation," *Transactions of the American I.E.E.*, III, 1954, 73, p. 799.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. R. T. Rushall and **J. S. Simons** (*in reply*): We must emphasize that the paper is concerned with one particular type of d.c. test, and its conclusions are not a condemnation of d.c. testing in general. A d.c. proof test is useful for evaluating some types of weakness when a comparable field distribution is obtainable, but for detecting major weaknesses such as large voids in h.v. stator insulation, which will fail under a.c. stress conditions, we consider that d.c. testing is useless. This is because the mechanism of breakdown under a.c. conditions—in this case internal discharge leading to a condition of thermal instability—is not reproduced when direct current is applied.

The results of d.c. tests on stator windings reported by Messrs. Jones, Stannett, Smith, Milne and Carfrae are most valuable contributions to the subject, and in general support the conclusions of the paper.

Many speakers refer to the damaging effect of a.c. over-voltage tests on insulation. Our experience is that the standard over-voltage test of twice the rated voltage plus 1 kV for new well-consolidated insulation results in a negligible amount of deterioration, and as some types of fault are revealed only by an a.c. proof test, we consider that this test is at present indispensable. It is not, in any case, usual to apply such a high test level to insulation after it has been in service.

Messrs. Jones, Edwards and Ellison suggest that a discharge detector would yield useful information, and Messrs. Smith and Milne give useful comment on the use of such equipments. Our experience is that it is very difficult to interpret discharge-detector responses when testing windings, because of difficulty in eliminating extraneous effects. One can use a probe to detect excessive end-winding discharges or to locate streamer discharges between coil and core. These streamers tend to swamp any response to internal discharges in the insulation. Alternatively, one can measure corona current by placing the detector in series with a filter at the h.v. end of the winding. Such a test gives an indication of the corona discharge throughout the winding, but is mostly an indication of corona at the line end.

We believe that this type of corona test is nevertheless likely to be of more practical value than attempts to measure individual discharge magnitudes, and that it may prove an alternative to the loss-angle/voltage test. Some promising results have already been obtained in France with such measurements.

Mr. Anscombe has dealt effectively with the point raised by Mr. Jones concerning the modifying effect of resistance grading on the direct-voltage distribution. The presence of such grading would tend to increase the discrepancy between a.c. and d.c. stress distributions, carrying the stress gradient further out in the end-winding.

In reply to Mr. Stannett, the curves in Fig. 15 were obtained when the insulation resistance was low, and consequently some drying out was taking place during the test. As mentioned in the paper, the winding was afterwards dried out and resulted in the curves shown in Fig. 16. An interval elapsed before the curves in Fig. 17 were obtained, and the higher currents there are attributed to re-absorption of moisture.

In reply to Messrs. Anscombe, Carfrae and McBain, all direct-current/voltage tests are particularly sensitive to the presence of moisture. This can be useful in affording an indication of the state of dryness of the insulation under known conditions of temperature and humidity. When not masked by the effect of moisture, d.c. absorption tests may indicate the degree of consolidation of the insulation, although this information may not indicate how long the insulation will operate satisfactorily.

In reply to Mr. Milne, the large currents measured when testing the unguarded coil are the result of a combination of distributed surface leakage over the end-winding together with concentrated intermittent leakage emanating from local discharges. No flaws in the end-winding insulation were detected, the local discharges being attributed to breakdown of high-resistance leakage paths between tapings, following the accumulation of charge locally.

In reply to Mr. McBain, approximately 6% of ripple was present in the open-circuit d.c. supply, but the large capacitance of the stator winding ensured very effective smoothing. Insufficient experience is available of the stress distribution in stator windings under impulse conditions, and much investigation is required before the usefulness of such a test can be assessed.

In reply to Mr. Ellison, no adequate test has yet appeared which seems capable of indicating the expectancy of life of insulation. The mechanisms of breakdown are complex and we feel that the most profitable information will be obtained from tests repeated during service life. Considerable information and data are necessary before results can be interpreted with confidence.

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CURRENT SUMMATIONS WITH CURRENT TRANSFORMERS

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The paper was first received 10*th February, and in revised form* 29*th March*, 1954. *It was published in June*, 1954, *and was read before the* MEASUREMENTS SECTION 1*st February, the* NORTH-WESTERN MEASUREMENTS GROUP 21*st January, and the* MERSEY AND NORTH WALES CENTRE 21*st March*, 1955.)

SUMMARY

The behaviour of current transformers in parallel, and of similar ircuits employing summation transformers, is studied for different onditions of load distribution.

After the existing theory concerning idle currents has been rejected is demonstrated that the overall error is very nearly constant for a iven total load, no matter how the current may be shared among the ne transformers. A complete equipment may thus be regarded as a ingle current transformer and the circuit parameters are considerably implified, enabling practical formulae to be established for deter-nining the overall errors.

In the latter part of the paper it is shown how the effective burdens n the individual transformers may be estimated and how test results t these burdens may be used to compute the overall errors. Worked xamples are given, together with confirming test results.

(1) INTRODUCTION

Current transformers may be used to provide a very accurate, heap, flexible, stable and permanent means of summing the urrents in a number of supply lines with little maintenance and o moving parts. Unfortunately, a prejudice exists against their se, chiefly because it is thought that the accuracy is impaired one or more of the lines is cut out of circuit. In many cases, ndeed, alarming conclusions have been reached which have led the complete rejection of current-transformer methods of ummation. The present study was begun with the intention of howing that the prejudice is based on a fallacy. This having een done, however, it was quickly realized that the circuit arameters were thereby made much less complicated, enabling mple methods to be developed for computing the overall ccuracy of current-transformer summation circuits. These are escribed in the last two Sections of the paper. Some of the onclusions reached, although primarily intended for use in netering problems, are also applicable to protection current ansformers working under steady-state conditions with un-aturated cores.

Many forms of balanced protection rely on the parallel con-ection of current transformers to sum the currents in the lines f a 3-phase system. Under healthy conditions there should be o current in the relay circuit, but in practice a small zero-phase-equence component flows, owing to differences in the errors f the transformers; the ability to arrange that this shall be a inimum requires a proper appreciation of the behaviour of e transformers, having regard to the special conditions under hich they operate.

(1.1) Purpose of Summation

A clear definition of the overall purpose of current summa-on will help to put the problem in its proper perspective. The oject of summation is to enable a number of currents in different eders to be regarded as one combined current in a single eder. If all the currents did, in fact, flow in one conductor, would be measured by a single current transformer connected rectly to its metering burden. It is, then, as a single current transformer that the whole summation equipment must be considered to act, and its performance should be judged on that basis. The equivalent single transformer has an overall ratio which is a simple function of the component ratios, and the primary current is the vector sum of all the feeder currents. For the arrangement to behave as a true current transformer, the overall error should depend only on the total load, and not on the way in which it is shared among the feeders. It will be shown that this ideal is approached very closely in theory and practice.

(1.2) Methods of Summation

The simplest method of summation is to surround all the feeders with a common ring-type current transformer, whose secondary then produces a current proportional to the vector sum of all the line currents. The inherent accuracy of this scheme is beyond question, but it is clearly impracticable when the feeders are more than a few inches apart, although it is common practice in protection when the ring transformer merely has to pass over a 3-phase cable.

The two other summation methods involving current trans-formers both require a separate transformer to be installed in each feeder concerned, and these are the methods which will be treated in the present paper.

The first is to connect all the secondaries in parallel to the measuring circuit, which carries the sum of the secondary currents. This is a simple and satisfactory solution when there are not too many feeders, but unless special ratio transformers are used the current in the burden may be quite large. It is essential for all the transformers to have the same nominal ratio, even if the ratings of the feeders are different.

In the second method a summation transformer is used to sum the secondary currents; this has as many primaries as there are feeders. Each primary is connected to a line-transformer secondary, and its number of turns is proportioned to corre-spond to the nominal ratio of that transformer. The secondary current of the summator is then proportional to the sum of the currents in the feeders.

The use of a summation transformer has several advantages compared with direct paralleling of the secondaries. First, it is much more flexible, and will deal, not only with line trans-formers of different ratios, but also with unequal secondary currents without any difficulty. This is most useful when one feeder is perhaps several hundred yards from the rest, enabling a 1-amp secondary to be used in order to keep the loss in the leads to a minimum.

Any number of feeders may be handled by a summation transformer without loss of accuracy, and the current in any part of the secondary circuits need not exceed 5 amp. Excellent performance may be obtained with an internal copper loss of about 5–6 watts, representing only an insignificant extra burden when shared among several line transformers. The total burden on any one line transformer is usually much less than with paralleled secondaries.

(1.3) Working Conditions

To ensure that suitably rated current transformers are chosen

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when using either the paralleled-secondary or summation transformer methods, it is necessary to pay proper attention to the rather unusual conditions under which they work.

In Sections 3 and 4 it is shown how the various equivalent burdens may be estimated. Methods are also given for determining the overall error from simple tests on the individual transformers, which is important because of the difficulty of carrying out a test on a complete summation equipment.

(2) THE EFFECTS OF IDLE FEEDERS

In this Section the behaviour of current transformers in parallel will be considered for different load distributions. The same arguments and conclusions apply equally to circuits employing a summation transformer. The generally accepted, but fallacious, case against summations with current transformers may be stated as follows:

Fig. 1 shows two current transformers connected in parallel

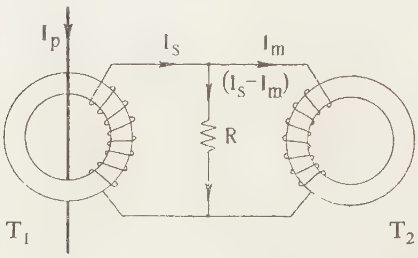

Fig. 1.—Parallel current transformers with one line idle.

to a common burden of R ohms, with current flowing only in the primary of transformer T_1. The secondary current passes mainly through R, but the burden voltage is impressed across the idle secondary of the other transformer, causing a small magnetizing current to flow in that winding. This current should have passed through the burden and therefore produces a direct error in measurement.

Pursuing the argument further, it is said that if there were, for instance, ten transformers in parallel, and only one was providing load current, each of the remaining nine idle secondaries would draw its own magnetizing current and the resulting accuracy would be very poor. This is tantamount to saying that if a succession of choke coils is connected across the secondary of a current transformer its accuracy is progressively worsened, and, as it stands, is undeniable. It does not, however, represent a valid approach to the problem, because it considers the transformers as separate and independent units, whereas they are really component parts of a single measuring device. Moreover, they are permanently connected to each other and their magnetizing currents are present all the time, whether they contribute any load current or not. Let us look a little more closely at Fig. 1.

The total error in measurement is the sum of the magnetizing currents of the individual transformers, which depend on the voltages which have to be induced in their secondaries. If we ignore the impedances of the secondary windings and connecting leads for the time being, exactly the same voltage is impressed across both secondaries. This depends solely on the current in the burden, which in turn is proportional only to the total current in the two feeders and is not affected by the manner in which it is divided between them.

For a given total load current, therefore, the two magnetizing currents, and consequently the overall error in measurement, have fixed values, and this applies even when one feeder carries all the current and the other is idle.

In practice, the impedances of the secondary windings and connecting leads form an appreciable part of the total and must be taken into account. How closely the ideal may be approached in practice depends on the relative value of the impedances in the different secondary circuits and the similarity of the performance curves of the transformers.

To study this problem, secondary circuits will be divided into two categories, namely

(*a*) Balanced circuits, in which the transformers all have the same errors and the impedances of the secondary circuits are in proportion to their rated primary currents. It should be noted that with paralleled secondaries this means equal impedances, since all the transformers must have the same ratio.

(*b*) Unbalanced circuits, in which either or both conditions for balance are unfulfilled.

(2.1) Balanced Secondary Circuits

The overall error of a group of parallel-connected transformers will be estimated first for equally distributed load and then for the same total load with some of the lines idle.

The error of a current transformer is the fraction of the primary current expended in magnetizing the core. This depends on the flux density in the core, or, more conveniently for the present analysis, on the voltage induced in the secondary winding. If, therefore, we assess the secondary induced voltages for the different load distributions, we have a means of comparing their magnetizing currents and subsequently the errors. In calculations of the voltages only the nominal current values need be considered, the error currents being very small in comparison.

Let n = Number of transformers in parallel.
k = Nominal ratio of each transformer.
I = Primary current in each transformer.
I_m = Magnetizing current in each for this condition referred to primary.
Z = Burden impedance.
Z_s = Impedance of remainder of each secondary circuit.

Then,

Total current being measured $= nI$

Total error current $= NI_m$

Overall error $$= \frac{nI_m}{nI} = \frac{I_m}{I} \quad . \quad (1)$$

Nominal burden current $= nI/k$

Burden voltage $= nZI/k$

Total e.m.f. induced in each secondary $= I(Z_s + nZ)/k$ (2)

The flux which produces this e.m.f. in each transformer is maintained by the magnetizing current I_m.

Next suppose that some of the feeders are idle and that the whole of the current nI is shared equally among the remainder. The nominal current in the burden, and therefore the voltage across it, is unchanged.

If a is the number of loaded feeders, the current in each is nI/a and the voltage drop in the secondary circuit of each is given by

$$\frac{InZ_s}{ka}$$

Add the burden voltage; then the total e.m.f. induced in each loaded secondary is

$$\frac{I}{k}\left(\frac{nZ_s}{a} + nZ\right) \quad . \quad . \quad . \quad . \quad . \quad (3)$$

In each idle secondary only a small magnetizing current flows and the voltage drop is negligible; consequently, the e.m.f.

duced in each is equal to the voltage across burden idle condary, i.e.

$$nZI/k \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

It is evident that the induced e.m.f. has increased in the aded transformers and decreased in the idle ones. Since the ange in flux density is not generally very great, it may be sumed with good accuracy that the magnetizing current anges proportionally to the induced voltage. Thus, the agnetizing current of each loaded transformer is

$$I_m \left[\frac{\text{expression (3)}}{\text{expression (2)}}\right] = I_m \times \frac{n(Z_s + aZ)}{a(Z_s + nZ)}$$

d the total magnetizing current for a loaded transformers is

$$I_m \times \frac{n(Z_s + aZ)}{(Z_s + nZ)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

milarly, the magnetizing current for $(n - a)$ idle trans-rmers is

$$I_m(n - a)\left[\frac{\text{expression (4)}}{\text{expression (2)}}\right] = I_m \times \frac{n^2Z - anZ}{(Z_s + nZ)} \quad . \quad (6)$$

dding expressions (5) and (6) gives the total magnetizing rrent for all transformers as

$$I_m\left[\frac{n(Z_s + aZ) + n^2Z - anZ}{Z_s + nZ}\right] = nI_m$$

Since the total current being measured has not changed, we ve,

$$\text{Overall error} = \frac{nI_m}{nI} = \frac{I_m}{I} \quad . \quad . \quad . \quad . \quad (7a)$$

ich is the same as for equally distributed loads.

This indicates that the overall error is unchanged no matter w many feeders may be idle. A similar treatment for circuits ploying a summation transformer gives the same result, and is also possible to show that the error is constant when the rrents in the different feeders are not in phase with each other. is reasonable to infer, therefore, that for balanced circuits e overall error is independent of the current distribution.

The test figures given in Table 1 amply confirm the theory. ey refer to a group of four similar 100/5-amp transformers th their secondaries connected in parallel to a resistance of l ohm. The overall ratio was thus 400/20 amp and the burden s 40 watts at rated current.

Transformers with larger errors than usual were deliberately osen, in order to magnify any differences which might appear. e measurements were made on an ordinary current-trans-

Table 1

Effect of Idle Feeders on Overall Error

Burden current	Equally loaded feeders		One idle feeder		Two idle feeders		Three idle feeders	
	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle
amp	%	min	%	min	%	min	%	min
6	−0·83	27	−0·83	27	−0·81	27	−0·78	27
5	−0·82	30	−0·83	29	−0·81	29	−0·78	29
4	−0·81	33	−0·81	33	−0·80	32	−0·76	32
3	−0·79	36	−0·79	36	−0·77	35	−0·74	35
2	−0·76	41	−0·76	40	−0·75	40	−0·72	39
1	−0·72	47	−0·72	46	−0·70	45	−0·67	45

former testing set and the maximum burden current it was possible to handle was 6 amp, or 30% of the rated 20 amp.

Since it was difficult to arrange four identical feeders in parallel, a special test procedure was adopted. The results given in the first column represent equally distributed load and were obtained with the four primaries in series, giving a test ratio of 100/20 amp. For the second column one primary was disconnected, leaving its secondary idle, and the tests were repeated for the same nominal burden currents. The test ratio was then 100/15 amp. The third and fourth columns were obtained by disconnecting two and three primaries respectively, giving test ratios of 100/10 and finally 100/5 amp, but each time the ratio and phase-angle errors were measured at the same burden currents, representing the same total loads in the four feeders.

(2.2) Unbalanced Secondary Circuits

When the transformers have different accuracies the changes in error may not cancel out so closely, because the poor ones vary more than the others when the current distribution is changed. A similar effect is produced when the secondary impedances differ, since a change in current then brings about unequal variations of the induced voltages in the secondary windings. In either case, or a combination of both, the overall error is not fixed but tends to change according to the current distribution among the feeders.

For the simple case of two parallel transformers the extremes of load sharing are

(a) All the current in the good transformer.
(b) All the current in the poor transformer.

The maximum change in the overall error that can occur between (a) and (b) is always less than the difference between the individual errors. Unless the difference is very large, which is most unusual in practice, the changes in error are small and may often be ignored.

Table 2

Unbalanced Transformers in Parallel

Rated current	Individual errors				Errors when in parallel					
	No. 1		No. 2		Equal loads		No. 2 idle		No. 1 idle	
	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle
%	%	min	%	min	%	min	%	min	%	min
60	−1·3	35	−0·56	17	−0·95	26	−1·0	26	−0·90	26
40	−1·5	50	−0·56	20	−1·05	35	−1·1	35	−1·0	34
20	−1·8	80	−0·53	25	−1·2	54	−1·3	55	−1·1	51
10	−2·15	125	−0·50	30	−1·35	80	−1·45	83	−1·2	83

This point is illustrated in Table 2, which gives the results of tests made on a metering transformer and one of coarse accuracy connected in parallel. The individual errors are given, in the first two columns, to show the big differences in quality between the two units. The last three columns give the overall performance with the transformers in parallel for equally distributed load and also for the two extreme conditions outlined above. The differences between the last three columns are small compared with the errors themselves, in spite of the severe conditions chosen for the test.

Much more important is the effect of having different amounts of turns compensation on the various transformers. When the natural errors of a current transformer are large it is common practice to reduce the ratio error by making the turns ratio a little greater than the nominal value. The magnetizing current is then larger than would appear from the measured errors of the transformer.

Table 3 gives a similar set of readings taken on the same two transformers with the secondary of the poorer one reduced from 80 to 79 turns. The ratio errors of this transformer, given in the first column, are seen to have changed by about 1·25% in a positive direction, as would be expected.

The overall ratio error for equally distributed load has changed only by about half of 1·25%, because only half the current is being supplied by the biased transformer.

When the good transformer is idle all the current comes from the turn-compensated transformer, and the ratio error is thus made more positive by about half the percentage turns bias. When the poor transformer is idle its turns compensation does not come into action at all, yet its full magnetizing current must still be supplied, and the ratio error shifts negatively by about half the percentage bias from the mean position. The conditions are then very much the same as for the fifth column of Table 2, with which the last column in Table 3 may be compared.

Table 3

Effect of Different Amounts of Turns Compensation

Rated current	Individual errors				Errors when in parallel					
	No. 1		No. 2		Equal loads		No. 2 idle		No. 1 idle	
	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle
%	%	min	%	min	%	min	%	min	%	min
60	−0·05	36	−0·56	17	−0·3	27	+0·1	28	−1·05	28
40	−0·25	50	−0·56	20	−0·45	35	0	36	−1·05	35
20	−0·65	83	−0·53	25	−0·63	55	−0·1	55	−1·15	53
10	−1·05	130	−0·50	30	−0·80	82	−0·35	86	−1·25	83

(2.3) Position of Parallel Connection

It is commonly supposed that the secondaries must be parallel connected at the burden and not at the transformer terminals. The reason given for this is that the voltage across the idle transformers is thereby reduced by the voltage drop which would otherwise occur in the common leads, causing a smaller magnetization current to be diverted from the burden.

Since the presence of idle feeders has been shown to have no appreciable effect on the overall error, it follows that the actual point of paralleling is unimportant and may therefore be chosen according to convenience.

If the transformers are close together and the meter some distance away, it is a little better to parallel at the transformer terminals rather than at the burden. In this way a greater proportion of the secondary voltage is common to all the tra[nsformers] and the variations in flux density for different curr[ent] distributions are reduced.

(3) CURRENT TRANSFORMERS IN PARALLEL

When current transformers are connected in parallel [the] overall ratio is the same as the ratio of the line transforme[rs] since the effect of paralleling is simply to multiply both [the] primary and secondary currents by the same number.

(3.1) Burden on Line Transformers

Let n = Number of transformers in parallel.

I_2 = Rated secondary current of each transformer.

Z = Impedance of burden.

Then

Rated burden current $= nI_2$ amperes

P.D. across burden $= nI_2Z$ volts

Contribution of each line transformer $= nI_2^2Z$ volt-ampe[res]

The effective burden on each transformer is thus n times w[hat] it would be if it alone were working into the same impedance.

This is a most important point which must be borne in m[ind] when choosing current transformers for use in parallel, oth[er]wise it may well happen that the rated burden will be grea[tly] exceeded with consequent loss in accuracy.

The total burden on any one transformer is nI_2^2Z added to [the] power lost in its own connecting leads. The ratio and pha[se] angle errors, measured at this burden, may be used in comput[ing] the overall error in the manner shown below.

(3.2) Overall Error

It has been shown that the overall error is practically in[de]pendent of the distribution of the current among the feed[ers]. Consequently, we may choose the most convenient conditi[on] for estimating its value. For a given total current the ove[rall] error is most easily determined when the feeder currents are equal and in phase with each other. Assuming that this is [so,] let

I_s = Corresponding nominal secondary current [of] each transformer.

r_1, r_2, etc. = Fractional ratio errors of the individual tra[ns]formers.

α_1, α_2, etc. = Phase angles, rad.

Then,

Nominal burden current $= nI_s$ amperes

$$\text{True burden current} = I_s(1 - r_1 - j\alpha_1) + I_s(1 - r_2 - j\alpha_2) + \ldots I_s(1 - r_n - j\alpha_n)$$
$$= I_s[n - (r_1 + r_2 \ldots + r_n) - j(\alpha_1 + \alpha_2 \ldots + \alpha_n)]$$

nd
$$\frac{\text{True current}}{\text{Nominal current}} = 1 - \left(\frac{r_1 + r_2 \ldots + r_n}{n}\right) - j\left(\frac{\alpha_1 + \alpha_2 \ldots + \alpha_n}{n}\right)$$

For ideal transformation the above fraction would be equal) unity. The term in the first bracket is the overall ratio error nd that in the second bracket the overall phase angle.

Rewriting, we may say,

$$\text{Overall ratio or phase error} = \frac{\text{Sum of individual errors}}{\text{Number of feeders}}$$

In other words, the overall error is equal to the average error, nd if identical transformers are used it is simply equal to the ror of one of them.

Although fractional errors were used to obtain this result, ny units may be employed in the final expression provided that ney are consistent. The answer will, of course, be in the same nits.

(3.3) Practical Application

The purpose of the following numerical example is to set out ne method of working and at the same time to verify the above onclusions. In practice, the line transformers are almost nvariably of the same design and have similar errors. The verall error is then, very simply, equal to that of an individual ransformer, and it is necessary only to ensure that the proper urden is used when testing it.

In order to test the theory as thoroughly as possible, four ransformers of different quality were chosen for the present xample, one being a Class-D unit of coarse accuracy which vould never be used for metering under normal circumstances.

The nominal ratios were 200/5 amp and the resistance of the eads was about 0·1 ohm for each transformer. The metering urden was also 0·1 ohm. Thus, for four transformers in arallel,

Effective burden on each transformer
$$= nZ + \text{lead resistance}$$
$$= 4 \times 0{\cdot}1 + 0{\cdot}1$$
$$= 0{\cdot}5 \text{ ohm.}$$

This represents 12·5 VA at 5 amp. The errors of the four transformers were measured at this burden and the results are given in the first four columns of Table 4. The fifth column gives the average error of the four.

Finally the transformers were connected in parallel to the common burden of 0·1 ohm and retested as a single unit. The results are given in the last column and are seen to agree very closely with the average values obtained from the individual tests.

(4) SUMMATION CURRENT TRANSFORMERS

Fig. 2 is a typical connection diagram for a 3-circuit summation transformer equipment. The secondary of each line transformer feeds an appropriate primary of the summator, the secondary of which supplies the burden.

The following symbols will be used for the general case of n circuits.

Let $k_1, k_2 \ldots k_n$ = Individual transformer ratios, primary to secondary.

$I_{p1}, I_{p2} \ldots I_{pn}$ = Rated primary currents.

$I_{s1}, I_{s2} \ldots I_{sn}$ = Rated secondary currents $= \frac{I_{p1}}{k_1}, \frac{I_{p2}}{k_2}$, etc.

$N_1, N_2 \ldots N_n$ = Corresponding numbers of turns on summator primaries.

N_s = Number of turns on secondary of summator.

I_s = Rated secondary current of summator.

K = Overall ratio of equipment.

Then
$$K = \frac{\text{Sum of all rated primary currents}}{\text{Rated secondary current of summator}}$$

For true summation the current in the measuring circuit must be a consistent fraction of the vector sum of all the line currents. This means that when all the line transformers are carrying full load the ampere-turns contributed by each to the summator must be proportional to its own rated primary current. It follows that the total ampere-turns on the summator bears the same proportion to the sum of all the rated primary currents.

Thus,
$$\frac{I_{s1}N_1}{I_{p1}} = \frac{I_{s2}N_2}{I_{p2}} \ldots = \frac{I_{sn}N_n}{I_{pn}} = \frac{I_sN_s}{\Sigma I_p} \quad . \quad . \quad . \quad (7b)$$

(4.1) Burden on each Line Transformer

The external burden on each line transformer comprises three parts:

(*a*) A share of the total volt-amperes in the secondary circuit of the summator.
(*b*) Loss in corresponding summator primary coil.
(*c*) Loss in connecting leads.

Table 4

Determination of Overall Errors of Paralleled Current Transformers

Rated current	Individual errors								Average errors		Overall test results	
	No. 1		No. 2		No. 3		No. 4					
	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle
%	%	min	%	min	%	min	%	min	%	min	%	min
30	−0·26	11	−2·7	115	−0·75	19	−0·38	13	−1·02	40	−1·06	39
25	−0·25	12	−3·0	130	−0·77	20	−0·37	14	−1·10	44	−1·10	44
20	−0·25	12	−3·2	155	−0·79	23	−0·37	16	−1·15	52	−1·16	51
15	−0·23	14	−3·5	180	−0·78	28	−0·36	18	−1·22	60	−1·20	60
10	−0·22	15	−3·9	240	−0·78	35	−0·34	20	−1·31	78	−1·30	75

The loss in the connecting leads is common to all current-transformer circuits and does not enter into the present analysis. Nevertheless it must be added to that due to the summator and its load to obtain the total burden at which the transformer operates.

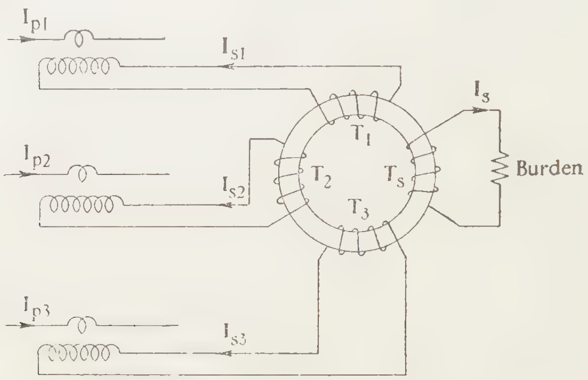

Fig. 2.—Connections for 3-circuit summation transformer.

It remains, then, to determine the effective burden imposed on each transformer by the summator and the measuring apparatus.

Let $R + jX$ = Burden impedance.
R_s = Resistance of summator secondary winding.
$R_1, R_2, \ldots R_n$ = Resistances of summator primaries.

The losses in the summator primary coils may be found by measuring their d.c. resistances and multiplying by the squares of the currents. Usually it is not necessary to be so precise, because the loss is only a small proportion of the total burden. If the current densities and mean turn lengths of the coils are assumed to be the same, which is approximately true, the copper loss in primary is proportional to its contributory ampere-turns.

If P is the total power loss in all the primary coils, the loss in the first primary is

$$\frac{I_{p1}}{\Sigma I_p} P \text{ watts} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

and similarly for the other coils.

The next step is to determine how the total volt-amperes expended in the secondary circuit of the summator are shared among the line transformers.

$$\text{Induced voltage per turn on summator} = \frac{I_s}{N_s}[R_s + (R + jX)]$$

$$\text{Induced voltage in first primary} = \frac{N_1 I_s}{N_s}[R_s + (R + jX)]$$

$$\text{Volt-ampere burden on first primary} = \frac{I_{s1}N_1 I_s}{N_s}[R_s + (R + jX)]$$

But, from expression (7b), $I_{s1}N_1 = \dfrac{I_{p1}I_s N_s}{\Sigma I_p}$

Substitution gives

$$\text{Volt-ampere burden on first primary} = \frac{I_{p1}}{\Sigma I_p} I_s^2 [R_s + (R + jX)] \quad . \quad . \quad . \quad . \quad (9)$$

Similar expressions hold for the remaining transformers. Adding expressions (8) and (9) and rearranging gives

Total burden on first line transformer

$$= \frac{I_{p1}}{\Sigma I_p}[(P + I_s^2 R_s) + I_s^2(R + jX)] \quad . \quad (10)$$

The first term in the square bracket is the total copper lo in all the summation-transformer windings, and this figure m either be supplied by the manufacturer or worked out from t resistances of the coils. The second term is the metering burd in volt-amperes.

The final expression may be written as

$$\text{Burden on any line transformer} = \frac{\text{Its rated primary current}}{\text{Sum of rated primary curren}}$$

$$\times \text{ Total volt-amperes in summator and its burd}$$

The energy lost in the connecting leads must be added to fi the total burden on the transformer. The ratio and phase-ang errors, measured at this burden, may be used in computing t overall error of the equipment in the manner about to described.

(4.2) Overall Errors

Because of the errors of the individual transformers, the vect sum of all the ampere-turns supplied to the summation tran former is not quite equal to its proper value. The differen will be called the combined error of the line transformers, a may be resolved into ratio and phase-angle components. T errors of the summation transformer itself must then added to the combined figure to obtain the overall error of t equipment.

Here the combined errors of the line transformers will determined with equal fractions of rated current flowing in ea of their primaries, all the currents having the same phase positi This is the simplest condition to deal with, and is permissib because, as for paralleled secondaries, the overall performan is nearly independent of the current distribution.

Let x = Fraction of rated current flowing in ea line transformer primary.
xI_{p1}, xI_{p2}, etc. = Primary currents of line transformers.
r_1, r_2, etc. = Fractional ratio errors.
α_1, α_2, etc. = Phase angles, rad.

Then the nominal secondary current of the first transformer $= x$

and the true secondary current of the first transformer

$$= xI_{s1}(1 - r_1 - j\alpha_1)$$

and similarly for the other transformers.

Next we have

Sum of nominal ampere-turns in summation-transform primaries

$$= xI_{s1}N + xI_{s2}N_2 \ldots + xI_{sn}N_n$$

But, from expression (7b),

$$I_{s1}N_1 = \frac{I_{p1}}{\Sigma I_p} I_s N_s, \text{ etc.}$$

Substituting and rearranging,

Sum of nominal ampere-turns

$$= xI_s N_s \left(\frac{I_{p1}}{\Sigma I_p} + \frac{I_{p2}}{\Sigma I_p} \ldots + \frac{I_{pn}}{\Sigma I_p}\right)$$

$$= xI_s N_s \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1$$

Now consider the actual ampere-turns supplied to the summ tion transformer.

Sum of actual ampere-turns

$$= xI_{s1}N_1(1 - r_1 - j\alpha_1) + xI_{s2}N_2(1 - r_2 - j\alpha_2) \ldots$$
$$+ xI_{sn}N_n(1 - r_n - j\alpha_n)$$

ubstituting for $I_{s1}N_1$, etc., as above, and rearranging gives

Sum of actual ampere-turns

$$= xI_sN_s\left[1 - \left(\frac{I_{p1}}{\Sigma I_p}r_1 + \frac{I_{p2}}{\Sigma I_p}r_2 \ldots + \frac{I_{pn}}{\Sigma I_p}r_n\right) - j\left(\frac{I_{p1}}{\Sigma I_p}\alpha_1 + \frac{I_{p2}}{\Sigma I_p}\alpha_2 \ldots + \frac{I_{pn}}{\Sigma I_p}\alpha_n\right)\right]$$

ividing by expression (5) gives

$$\frac{\text{True ampere-turns}}{\text{ominal ampere-turns}} = 1 - \left(\frac{I_{p1}}{\Sigma I_p}r_1 + \frac{I_{p2}}{\Sigma I_p}r_2 \ldots + \frac{I_{pn}}{\Sigma I_p}r_n\right) - j\left(\frac{I_{p1}}{\Sigma I_p}\alpha_1 + \frac{I_{p2}}{\Sigma I_t}\alpha_2 \ldots \frac{I_{pn}}{\Sigma I_p}\alpha_n\right) \quad . \quad (12)$$

The terms in the first and second brackets of this expression ve the combined ratio error and phase-angle respectively of l the line transformers.

hus,

$$\text{Combined ratio error} = \frac{I_{p1}}{\Sigma I_p}r_1 + \frac{I_{p2}}{\Sigma I_p}r_2 \ldots + \frac{I_{pn}}{\Sigma I_p}r_n$$

$$\text{Combined phase-angle} = \frac{I_{p1}}{\Sigma I_p}\alpha_1 + \frac{I_{p2}}{\Sigma I_p}\alpha_2 \ldots + \frac{I_{pn}}{\Sigma I_p}\alpha_n$$

For the contribution made by an individual transformer we ay write, for either ratio or phase-angle error,

Contribution of one transformer to combined error

$$= \text{Its own error} \times \frac{\text{Its own rated primary current}}{\text{Sum of rated primary currents}}$$

Although fractional errors were defined initially, any con-enient units may be used in the final calculation, provided at they are consistent. The answer will then be in the same its.

Very often in practice all the line transformers have the same tio. The expressions then reduce to

$$\text{Combined error} = \frac{\text{Sum of individual errors}}{\text{Number of line transformers}}$$

other words, the combined error is the average error. If all e transformers are identical, the combined error is equal to e error of one transformer.

The errors of the summation transformer itself, measured its working burden, must be determined separately and lded to the combined figure to obtain the overall error of the uipment.

(4.3) **Practical Procedure**

The general procedure for determining the overall error mprises the following steps:

(*a*) Estimation of the working burden of each line transformer.
(*b*) Testing of each transformer at its working burden.
(*c*) Estimation of the combined errors of the line transformers.
(*d*) Testing of summation transformer at its working burden.
(*e*) Adding the results of (*c*) and (*d*) to obtain the overall error of equipment.

When all the line transformers have the same ratio and per-rmance, the operations (*a*) and (*b*) are much simplified while disappears entirely. The total burden is then shared equally the line transformers and only one of them need be tested, e results of which may be added directly to the errors of the mmation transformer.

The following example was worked out for a more compli-ted case, with three different-ratio line transformers having unequal errors, in order to show the complete procedure. To enable the example to be used as a model, all the steps are included, no matter how simple. Reasonable approximations are made when necessary without further comment, and although the working out may appear rather long it is really very simple and straightforward, involving only mental arithmetic.

The circuit particulars were as follows:

Line transformer ratios = 100/5, 200/5, 300/5 amp.
Summation transformer ratio = 5/5 amp.
Metering burden = 15 VA (non-inductive).
Internal losses of summation transformer $\simeq$ 6 watts.
Losses in leads $\simeq$ 2 watts per transformer.

The overall ratio was therefore 600/5 amp, and ΣI_p was 600 amp.

(4.4) **Working Burdens**

A total of 21 watts is lost in the summation transformer and its burden, and is shared among the line transformers as follows:

$$100/5 \text{ burden} = 21 \times \frac{100}{600} = 3{\cdot}5 + 2 = 5{\cdot}5 \text{ watts.}$$

$$200/5 \text{ burden} = 21 \times \frac{200}{600} = 7 + 2 = 9 \text{ watts.}$$

$$300/5 \text{ burden} = 21 \times \frac{300}{600} = 10{\cdot}5 + 2 = 12{\cdot}5 \text{ watts.}$$

In each case the leads loss of 2 watts has been added to obtain the total burden. The measured errors of the three transformers are given in Table 5.

Table 5

MEASURED ERRORS OF LINE TRANSFORMERS

Rated current	100/5 at 5·5 VA		200/5 at 9 VA		300/5 at 12·5 VA	
	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle
%	%	min	%	min	%	min
100	−0·38	11	−0·50	27	−0·55	27
60	−0·38	15	−0·57	14	−0·55	17
20	−0·33	22	−0·63	21	−0·64	16
10	−0·31	25	−0·62	30	−0·66	22

The combined errors of the line transformers are worked out in Table 6, the individual contributions being estimated as follows:

Ratio	*Contribution to Combined Error*
100/5	100/600 of its own error.
200/5	200/600 of its own error.
300/5	300/600 of its own error.

Table 6

CALCULATION OF COMBINED ERROR

Rated current	Individual contributions						Combined errors	
	100/5		200/5		300/5			
	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle
%	%	min	%	min	%	min	%	min
100	−0·06	2	−0·17	9	−0·28	14	−0·51	25
60	−0·06	3	−0·19	5	−0·28	8	−0·53	16
20	−0·06	4	−0·21	7	−0·32	8	−0·59	19
10	−0·05	4	−0·21	10	−0·33	11	−0·59	25

In Table 7 the final stage of the process is shown. The first column contains the errors of the summation transformer measured at 15 VA, the second gives the combined errors taken from Table 6, while the third is the sum of the first two and gives the calculated overall performance of the whole equipment.

Table 7

OVERALL ERRORS OF SUMMATION EQUIPMENT

Rated current	Summation transformer errors, 15 VA		Combined errors of line current transformers		Overall errors			
					Calculated		Measured	
	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle	Ratio error	Phase angle
%	%	min	%	min	%	min	%	min
100	−0·45	17	−0·51	25	−0·96	42	−0·96	41
60	−0·48	10	−0·53	16	−1·01	26	−1·0	25
20	−0·51	16	−0·61	19	−1·12	35	−1·1	34
10	−0·47	24	−0·57	25	−1·14	49	−1·1	48

Finally all the transformers were connected and the overall errors measured. This would normally be a difficult task with unequal-ratio transformers. However, since ring transformers were purposely chosen for the case in question, it was a simple matter to convert them all to the same ratio, 100/5 amp, by winding two and three primary turns respectively on the 200/5- and 300/5-amp transformers. The three were then connected in series, making the equivalent overall ratio 100/5 amp, and the primary current was tested against the secondary current of the summation transformer.

The last column of Table 7 gives the measured overall errors, which agree very well with the calculated values and thus confirm the theory.

(5) CONCLUSIONS

A group of current transformers connected in parallel, or to a summation transformer, may be considered to act as a sin current transformer.

If the secondary circuits are reasonably balanced the over error for a given total load is a consistent quantity and is ve nearly independent of the distribution of current among t primary windings. If the secondary circuits are heavily u balanced the overall error is not quite constant for differe load distributions, but the changes are small unless the tra formers have unequal amounts of turns compensation. In th case the ratio error varies according to the current distributic and the maximum inconsistency is about equal to the differen in the turns compensation.

Using the formulae given in Sections 3 and 4 the effecti working burden on each transformer may be estimated, a individual test results at those burdens may be used to determi the overall errors of the system.

With transformers in parallel, the actual parallel connecti can be made at any convenient point between the transform terminals without appreciably affecting the errors.

(6) REFERENCES

(1) HAGUE, B.: "Instrument Transformers" (Pitman, Londc 1936), p. 147.

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(3) GOLDS, L. B. S., and LIPMAN, C. L.: "A Modern Eart Fault Relay Equipment for use on Systems protected Petersen Coils," *Journal I.E.E.*, 1944, **91**, Part II, p. 377.

(4) HILL, E. W., and SHOTTER, G. F.: "Current Transform Summations," *ibid.*, 1931, **69**, p. 1251.

(5) WIGGINS, A. M.: "Parallel Operation of Current Tran formers for Totalizing Two or More Circuits," *Electric Journal*, 1929, **26**, p. 379.

DISCUSSION BEFORE THE MEASUREMENTS SECTION, 1ST FEBRUARY, 1955

Dr. A. H. M. Arnold: The author has written a persuasive paper advocating the use of current transformers for current summation. In Section 3.1, however, he could easily make out a better case. A certain apparent power, say x volt-amperes, is required to operate an instrument. If x current transformers are used with their secondary windings in parallel to supply this apparent power, each transformer is only required to supply x/n volt-amperes. The burden on each transformer is thus continually decreased as the number in parallel is increased, and it will eventually approximate to that of the internal burden and connecting leads only.

When the method shown in Fig. 2 is used the losses in the summation transformer have to be provided, so that the practical advantages of this additional transformation stage have to be balanced against the disadvantage of supplying a larger burden.

Mr. C. Ryder: In the Introduction the author states that the general conclusions also apply to protective transformers. Then he makes the proviso that the conditions are steady-state ones and he also assumes that the cores do not become saturated. These limitations cannot receive too much emphasis when protective gear is considered, because with modern protective schemes, instantaneous relays are used where possible to give rapid clearance of faults. In those circumstances we are more concerned with transient conditions than steady-state ones, and transformers that might otherwise be good under symmetrical conditions can easily give trouble if there is any asymmetry.

Mr. H. S. Petch: The author should not have made a reference to protective current transformers, because only in t limited case mentioned in Reference 3 of the paper can stead state conditions be assumed to exist. The principles outlin in the paper can only be applied to protective current tran formers if they have non-magnetic cores. Protective syster using such transformers exist, but the current transformers a then connected in series.

The author has omitted to mention that the use of paral current transformers or summation current transformers f the metering of parallel circuits presupposes that those circu will remain in parallel at all times.

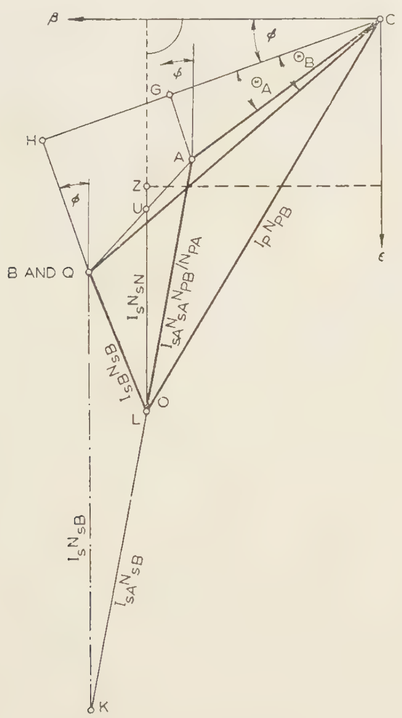
Mr. F. Byrne: Where a supply of electricity is provided, it not unusual to allow sufficient plant capacity to meet the requir ments with the largest unit out of service. For example, if tv transformer circuits of equal rating are provided, the effecti service capacity is only regarded as that of one transforme In a summation scheme applied to such a service, the seconda current in the summation circuit will not exceed the equivale of the primary current in one circuit. Therefore, the autho analysis, in which he assumes that both circuits are fully loade may not be true. In Section 2.1 he suggests that with 100/5 an current transformers, the effective combined ratio would 200/10 amp, but in fact the normal secondary current is or 5 amp. In these circumstances, the scale of errors should modified by comparing the overall errors at 50% of the rat

urrent with the individual errors at 100% rated current and so on. If three circuits are in parallel the comparison should be nade with the overall errors at 66% of the rated current.

Dr. A. A. Halacsy (*communicated*): Table 4 shows excellent greement between the calculated and measured errors of four urrent transformers with their secondary windings paralleled nd presumably with the primary windings connected in series or the test. Simple arithmetic can be used to calculate the rrors of the set in this particular case only because all four urrent transformers have no or equal turn compensation, eeping the secondary-turn numbers equal. The statement in ection 3.2 to the effect that the overall ratio or phase-angle rror is equal to the average of the individual ones is a corollary f the basic rule of vectorial summation in such a case.

The calculation is not so simple if the paralleled current ransformers differ in their turn compensation as demonstrated n Table 3. In Section 2.2 some guidance is given on estimating he error in such a case; a mathematical treatment, however, is voided and for good reason. Simple arithmetic does not help ecause of the vectorial nature of the problem. My vectorial olution* may contribute to the present paper.

The general vector diagram of the ampere-turns of two current ransformers A and B, with their secondary windings paralleled s shown in Fig. A. The total error CZ is resolved into the ε



ig. A.—Vector diagram of the m.m.f. of two current transformers with their secondary windings in parallel, and their primary windings in series.

I = Current.
N = Number of turns.
Subscripts p, s, N, A and B refer to primary, secondary, nominal, current transrmer A, and current transformer B, respectively.

atio error and β phase-angle error. Simple averaging would esult in the error CU instead of CZ. The difference UZ may e considerable in practical cases.

A graphical method of calculation was given in the quoted rticle.* Fig. B compares calculation and test results in the orm of a Moellinger–Gewecke diagram reprinted from that ource.

* Halacsy, A. A.: "Current Transformers and Their Operation," *Electrical Times*, 52, **121**, p. 1153.

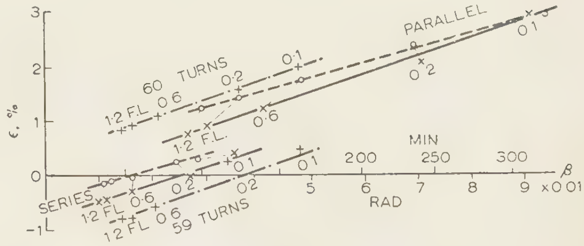


Fig. B.

——— Calculated errors.
— — Measured errors of a set of two current transformers with their primary windings in series and their secondary windings as indicated.
– – – – Calculated errors of the individual current transformers.

Mr. J. M. Vanderleck (*Canada: communicated*): Some of the statements in the paper, which appear to contradict commonly accepted ideas, warrant close examination. For example, with regard to current transformers connected in parallel, the author states that "it follows that the actual point of paralleling is unimportant and may therefore be chosen according to convenience." This is obviously misleading without the stipulation that it applies only when the effective burden on each transformer remains unchanged, the effective burden of a transformer in a group of n transformers being defined as the impedance of the leads which carry only the secondary current of the said transformer, together with n times the impedance of that burden which carries the current of all n transformers. Consequently, for two adjacent current transformers, if the position of paralleling is moved from a remote point to one close to the transformer terminals, the two pairs of secondary leads between the transformers and the remote point should still be used to keep the effective burden the same. Then the ratio error and phase angle will not change. This example illustrates the fact that copper cannot be saved by paralleling transformers close to the secondary terminals if the ratio and phase angle are not to be affected.

The author demonstrates mathematically in Section 2.1 that the overall error is unchanged no matter how many feeders may be idle. This is based on the premiss that the magnetizing current changes proportionally to the induced voltage. In normal current-transformer applications, the magnetizing current does not increase as fast as the induced voltage, owing to the increasing permeability of the core. It can be shown that the result will be to reduce the ratio error and phase angle, the greater the unbalance between feeders, and Table 1 illustrates this point. The ratio error and phase angle are a minimum when all except one of the feeders are idle.

The information in the paper is applicable to a common method of measuring the current in a line connected to a busbar, wherein current transformers are inserted in the busbar on both sides of the line and the secondary windings are paralleled to produce a secondary current representing the line current. Current unbalance between the two current transformers can exceed that for the case of two parallel feeders, because the current may not only fall to zero in one of the busbar current transformers, but may even reverse. The extreme case is when the line is open and current still flows in the busbar, when the overall ratio error is infinite and the overall phase angle is meaningless. For this extreme case, the practical effects of ratio error and phase angle of the two transformers are readily comprehended. However, when the current in the line is small and the busbar current is large, it would be interesting to know the value of the maximum overall ratio error and the phase angle. The paper does not cover this situation.

In Section 2.2 it is stated that the maximum change in overall

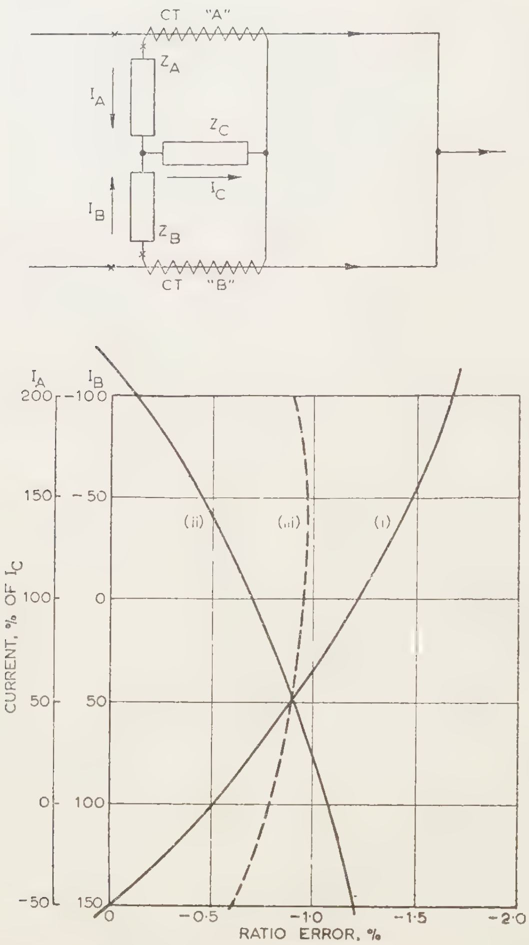


Fig. C.—Graphical analysis of the operation of two current transformers in parallel.

I_C is constant.
I_A and I_B are in phase.
Both current transformers have the same turns compensation.
(i) Ratio error of current transformer A as a percentage of $I_C/2$.
(ii) Ratio error of current transformer B as a percentage of $I_C/2$.
(iii) Overall ratio error as a percentage of I_C.

Burden on current transformer A $= Z_A + \frac{I_C}{I_A}Z_C$.

Burden on current transformer $B = Z_B + \frac{I_C}{I_B}Z_C$.

error which can occur between the extremes of load sharing is always less than the difference between the individual errors. (Presumably the individual errors are measured with balanced currents in the individual transformers, and with the effective burden.) This statement is supported by test results, but not by theory. For example, theory indicates the possibility of having two transformers of different excitation characteristics but which have the same individual ratio errors with balanced current, because of burden differences. Fig. C shows that the ratio error will change when all the current flows in one transformer. Obviously the statement does not hold for this example.

In Fig. C the overall ratio error is considered as the average of two components which are due to the exciting currents in current transformers A and B, respectively. The components of the overall ratio error are considered as percentages of $I_C/2$ rather than I_C merely to obtain the overall error from the average of the components rather than the sum. Obviously, the curve marked (i) is not the ratio error of current transformer A.

This graphical method of analysis demonstrates why the changes in overall ratio error are small, as stated by the author. The method also gives an indication of the changes in overall ratio error when the current in one current transformer reverses. The test data in Table A reveal that such changes are also small.

Table A

230 kV Bushing Current Transformers, Mumetal Core, Ratio: 600/5 amp. Frequency: 60 c/s. Connected in parallel. Summed Primary Current: 60 amp

Current in transformer A	Current in transformer B	Overall values	
		Ratio error	Phase angle
amp	amp	%	min
+30	+30	−0·27	+13
+60	0	−0·26	+13
+660	−600	−0·08	0

This supports the author's conclusion that transformers connected in parallel can be expected to have an overall ratio error and phase angle not far different from the average error of individual transformers when connected to their effective burdens.

[The author's reply to the above discussion will be found on page 593.]

NORTH-WESTERN MEASUREMENTS GROUP, AT MANCHESTER, 25TH JANUARY, 1955

Mr. O. Howarth: The method described by the author can sometimes be used in conjunction with mechanical summation. For example, two or more feeders terminating on a section of busbars with a similar arrangement on another section separated by a section switch which will normally be open can be summated by using a double 3-phase meter and summing the currents from one section on to one side and from the other section on to the other side of the double 3-phase meter. This makes an economic and reliable arrangement and avoids the use of impulsing meters, with their additional complications. The advent of Mumetal greatly increased the possibilities of the application of the principle of summating, owing to the greatly increased accuracy of current transformers.

How far is it valid to assume a linear relation between the exciting current of a current transformer and the voltage? If the exciting-current/voltage curve follows the usual shape and bends over, connection of the current transformers in parallel at the instrument or meter will result in smaller errors than if they are connected in parallel at the transformers, although the resultant error will not be so readily predictable or so consistent under different load distribution amongst the current transformers.

Could the author explain under what circumstances the use of a summation current transformer results in greater accuracy than paralleling the current-transformer secondary windings on the meter? Could the author clarify statements (*a*) and (*b*) in Section 2? Whilst all transformers must have the same ratio they need not have the same rating. For example, a 200/5 amp and a 100/2·5 amp current transformer could be summated.

Wherever the secondary windings are connected in parallel it is important to have the same total copper section between the current transformers and the meter if the same error is to result.

There will inevitably be diversity in the feeder loadings, and it is important to allow for this diversity by suiting the meter rating to the maximum load and not to the sum of the currents

ansformer primary ratings, otherwise maximum-demand idicator readings will be in the lower part of the range with onsequent loss of accuracy.

Mr. M. W. Sheppard: I do not understand the reference in ne Summary to the "existing theory concerning idle currents," nce I cannot find anything in the paper which conflicts with stablished practice, and the References do not produce nlightenment.

I can only assume that some confusion exists between the ifferent requirements of current transformers used for summating currents for metering purposes as distinct from current ansformers used for summating currents for protective purposes.

The principle is the same in both circuits, and the absolute rrors of the group of current transformers will be approximately equal to the error of one current transformer multiplied y the number of current transformers in circuit, if it is assumed nat they are identical and that the same burden and primary mpere-turns are considered in each case. With protective urrent transformers it is necessary to produce a definite current order to operate the relay at a given setting, and the equivalent urden at the rated current might be of the order of 100 VA. lso the current transformers are often required to remain elow the level of magnetic saturation for currents up to 20 mes the rated current, and hence the effects of "idle currents" re very important when evaluating the absolute error of the urrent transformers as a group.

Similar considerations also apply when estimating the errors f a group of current transformers summating for metering urposes, but it is not now essential to produce a definite esultant current, since the meter will register any current within s working range, and provided that the absolute current-ansformer error is within approximately 5%, the meter can be alibrated to give correct registration.

It is important, however, in view of the straight-line characeristics of the modern meter, that the error should be constant or all secondary currents, as any variation in current-transformer rror cannot be compensated for by normal means and will ppear as incorrect registration. Hence it is essential that the bsolute current-transformer error should be constant with a iven value of primary ampere-turns, no matter in what proortion the primary ampere-turns are shared between the current ansformers.

Practically the whole of the paper is devoted to consideration f this point, and it is obvious that, if the effect of the current-ansformer secondary circuit is neglected, a given current nrough a constant burden will produce a fixed voltage across ne current-transformer secondary terminals and hence a fixed agnetic flux in the respective cores. Thus the exciting m.m.f. also fixed, and as the primary ampere-turns are the vector ım of the secondary ampere-turns and the exciting ampere-ırns, the primary ampere-turns will have a definite value no atter in what proportion they are shared between the current ansformers.

Therefore, how far are we justified in minimizing the effect of e secondary-circuit impedance? The author deals with this pect at length, but I feel that the argument would be more onvincing if a description of the current transformers used in e experiment were given, together with their characteristics. particular, it would appear desirable to include a number of gh-reactance current transformers in the test, as the impression ined from the paper is that ring-type current transformers ıly have been considered.

If a group of current transformers of the high-reactance type are considered to be feeding into a low burden consisting of one meter coil, there is a wide difference between the flux density in the "loaded" current transformer and that in the idle current transformers. It is doubtful whether the simple formula in Section 3.2 would be sufficiently accurate to give a reasonable assessment of the overall errors.

Throughout the paper the expression "magnetizing current" is used when it is evident that the author means the "exciting current," and it would be necessary to break this down into its active and reactive components before embarking upon any calculation of errors. If the current transformers in question are of the high-reactance type, many other factors would have to be taken into consideration, and the formulae would become very complex.

The author's remark on the effective burden (Section 3.1) should be particularly emphasized, as it is a factor which can easily be overlooked when considering the effect upon the error of individual transformers of summating several current transformers.

Mr. N. Ashton: The author has given a satisfactory explanation of the effects of current transformers in idle feeders, and has emphasized in Section 1.1 that the performance should be judged on the basis of an equivalent single transformer. He could have pursued the argument further by indicating that an error which might appear large as a percentage of the rated current of one line transformer might be quite acceptable when considered in relation to the total current to be metered.

I should like the author to explain the statement at the end of Section 1.2 that the total burden on any one line transformer is usually much less when a summation transformer is used than with paralleled secondary windings, since this appears to be correct only in situations where the connecting leads carrying the summated current of paralleled current transformers present a greater burden than would be imposed by a summation transformer.

The statement in Section 3.1 regarding the burden on transformers with paralleled secondary windings is misleading in that it infers that the burden per transformer is proportional to the number of transformers in parallel, whereas, since Z is approximately inversely proportional to N^2, the converse is the case.

The author has confined his examples to feeders of additive power flow, and has not mentioned the conditions when the power flow in one or more feeders is reversed. An interesting phenomenon sometimes occurs in such situations. The secondary current from the subtracting current transformer is reversed in phase with respect to the burden voltage, so that it is possible for this current transformer to feed power into the line. Has the author had any experience of such a mode of operation?

I have sometimes been asked to design summation current transformers for power measurement which would compensate for feeders working at different voltages, e.g. 6·6 and 11 kV, and I have found that it is not always realized that the accuracy is somewhat dependent on the power transformers controlling the voltage ratios of the feeders. Accurate metering by such means appears to be impossible, but I should like the author's views on this matter.

[The author's reply to the above discussion will be found on page 593.]

MERSEY AND NORTH WALES CENTRE, AT LIVERPOOL, 21ST MARCH, 1955

Mr. J. S. Wilson: Part of the difficulty of understanding transformers probably arises from the use of volt-amperes as a means of specifying rated load. Although this method is specified by the B.S.I., I think it causes confusion. The author himself refers to burdens in terms of volt-amperes in Section 3.1, and in terms of ohms in Section 3.3, whilst in describing an example similar to that of Fig. 1 he uses volts. It would seem that considerable advantage could be gained by expressing the rating of the transformer in terms of volts at the rated current.

This method would clarify the condition when an earth-fault relay having a rating of 2 VA at 0·5 amp (4 volts) has been connected to a transformer rated at 5 VA at 5 amp (1 volt).

The author mentions the increase of burden which occurs when several current transformers supply a single load (see Section 3.1). I think it most unlikely that the summated load will be greater than the total of the individual main transformer ratings. However, it is possible that a 15 VA (1 volt) 15 amp summated load may be fed by two transformers rated at 15 VA (3 volts) at 5 amp and one rated at $2\frac{1}{2}$ VA ($\frac{1}{2}$ volt) at 5 amp. The danger of such an arrangement is more readily observed when the ratings are given in terms of volts.

No standard designation is used on the rating plates of summation transformers. Has the author any alternative to the $5 + 5 + 5/5$ rating frequently found? One suggestion employs the fractional basis $1/1 + 1/5 + (5/5)/5$. The numerator designates the rated primary current whilst the denominator represents the relationship which can exist between the primaries. In the example quoted the transformer could be used with either of the following groups: 20/1; 100/1; 100/5 or 100/1; 500/1; 500/5. Would the author criticize this form of rating?

I am sure the author will agree that in most cases little is known of the main transformers apart from the turns ratio and, in a few cases, the accuracy. The saturation voltage or whether there is already some connected load is generally not known. With only a knowledge of the primary turns ratios, does the author think there should be any restriction on the number of primary windings associated with a summation transformer? If ten primaries are to be summated would there be any advantage in summating first in two groups of five and finally summating the output of those two groups in a third summation transformer?

Mr. J. B. Lancaster: If one specifies a current transformer for a larger burden than is necessary in the initial installation, and thus making provision for future additional burden, there is a corresponding disadvantage inasmuch as the initial accuracy is reduced. This effect, I believe, arises out of the turns compensation being provided for the rated burden, and I would be interested to know whether this effect also applies, and whether it is more or less serious, with current-summation transformers.

There are many applications of summation transformers in connection with protective equipment in which the primary windings are connected in a manner analogous to an auto-transformer. Do the author's comments apply equally to that type of transformer as to transformers with separate primary windings?

On the system with which I am associated quite a number of summation transformers are used, and in many cases these summate currents in different directions, i.e. to indicate the local consumption at a substation with several incoming feeders, local transformer feeders and some outgoing feeders. Do the diagrams and reasoning apply equally to reverse currents, or are any material errors introduced?

Mr. E. P. Hill: Fig. 1 shows two current transformers in parallel; what would be the effect of a short-circuit upon the subsequent accuracy of the unloaded current transforme[r]. Under short-circuit conditions the loaded transformer wou[ld] supply a heavy distorted magnetizing current to the unload[ed] transformer, which could magnetize the core in a certain directi[on] and produce temporary inaccuracy. Would the use of mode[rn] magnetic materials for the transformer core tend to increa[se] this inaccuracy, and has the author any actual experience of su[ch] conditions?

Mr. F. B. Wollaston: I believe that the errors of current tran[s]formers are due largely to the loss of the iron circuits, so tha[t I] cannot understand why the errors should not vary with t[he] number of transformers in circuit. Since each transformer w[ill] be working at a normal flux density, the errors of each w[ill] become additive in the group. The author's experiments indica[te] that there is no change of error with change of loading o[f] individual feeders when transformers are either connected [in] parallel or through a summation transformer to a single measuri[ng] device. This may well be so, but it must be borne in mind th[at] the overall error becomes increasingly large according to t[he] number of circuits summated, and that the measuring device [is] seldom sufficiently flexible in calibration to correct for lar[ge] errors and still maintain an overall high accuracy.

When summation current transformers are made up to cov[er] a large number of circuits it becomes increasingly difficult [to] keep leakage reactance low, so that further errors are introduce[d]. This seems to clash with the author's ideas on the number [of] circuits which can be conveniently summated by means [of] summation current transformers.

I appreciate that from an economic point of view the sum[]mation current transformer and summation by paralleli[ng] current transformers has an important place in metering, bu[t I] feel that the paper places too much emphasis on the impressi[on] that high accuracy may be attained by this method.

Mr. P. d'E. Stowell: Summation is usually required of pow[er] and/or energy, and current summation is strictly usable only [if] there is no discrepancy either in magnitude or phase between t[he] voltages associated with all of the circuits to be summate[d]. Where energy is the primary quantity to be summated the counti[ng] of impulses representing discrete energy quotas has much [to] commend it as having the fewest limitations, e.g. distance.

Although accuracy is not impaired when one circuit is unload[ed] or is carrying reverse current, when the circuit is unloaded, sho[rt-]circuited and earthed the primary of one or more of the li[ne] current transformers could be short-circuited through [an] impedance low enough to have a very material effect on t[he] accuracy of the complete system; in the limit it could suppre[ss] its operation entirely. The line current transformers of t[he] appropriate circuit could have their secondaries disconnected fro[m] the rest of the summation system, but this introduces practic[al] problems, e.g. that of ensuring that the disconnection is, [in] fact, made and equally of ensuring that the correct connectio[ns] are subsequently restored.

However, the short-circuiting and earthing points may [be] insufficiently close in practice for the impedance across t[he] primary to be low enough to have a significant effect on t[he] operation of the summation system. The author's commen[ts] on this would be valuable. The effect is sometimes claimed [as] justification for using a summation transformer instead [of] paralleled secondaries, but I find it difficult to concede this, f[or] if the summation transformer is not to introduce und[ue] inaccuracy and additional burdens, it is inevitable that it mu[st] have very low inter-winding reactances, which would prevent [it] providing any material relief.

I can accept only one of the author's claims in Section 1

mely that a summation transformer permits a ratio change tween any or all of the main current transformers and the rden. Wherever this is unnecessary or can be avoided, a mmation transformer has definite disadvantages, for it introces its own errors and increases the total burden to be supplied, th consequent increase in the basic error of the line current ansformers. The author's statement that a summation transrmer can be used without loss of accuracy is therefore misading, as is his contention that a loss of 5 or 6 watts in the mmation transformer is an insignificant additional burden, nce the total meter burden seldom exceeds a figure of this order. oreover, I find the statement that "the total burden on any e line current transformer, when a summation transformer is ed, is usually much less than with paralleled secondaries," uite incomprehensible.

When current summation with current transformers is applible, I prefer to parallel the secondaries direct, and I would use a mmation transformer only where an additional ratio change is avoidable. Moreover, when all circuits are put through a mmation transformer purely to equate the ratios of one line rrent transformer with the others, it would be better to use auxiliary transformer and confine it specifically to the circuit ith the odd ratio.

In Section 2.3 the author denies that, in order to reduce the voltage across any idle transformers, it is better to parallel secondaries at the burden rather than at the current-transformer terminals. Then follows a correct statement that, since idle transformers do not appreciably affect the errors, the point of paralleling is unimportant; it is succeeded by a statement that it is a little better to parallel at the transformer terminals rather than at the burden. The whole argument seems illogical, as the reason given for refuting the first opinion is just as good a reason for rejecting the second. If the author had included a proviso that the same total amount of copper should be used for leads regardless of the point of paralleling, I would agree that one cannot reach a conclusion that it is a little better at one place than at any other. But it would not be so easy in practice to ensure that the leads were run in accordance with the proviso without a detailed specification. In practice, a pair of leads, say 7/·029 in, would be provided from each current transformer to the point of paralleling and another pair, also of 7/·029 in, from that point to the burden. On the hypothesis of uniform conductor area in all leads throughout, the nearer the point of paralleling is to the burden, the less is the total burden on each current transformer (as is clearly shown by Section 3.1), hence the less are the basic errors. One is therefore more likely to get the best results by thinking in terms of paralleling normally at the burden.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSIONS

Mr. A. Hobson (*in reply*): The main arguments in the paper ave not been disputed, although they contradict some longtablished views, and the discussion comprises criticism of etails together with many useful observations.

Dr. Arnold is undoubtedly right in what he says, although duction of burden is only an incidental point.

Mr. Ryder's remarks are pertinent, but I cannot fully agree ith Mr. Petch. In balanced protection much trouble has been used by incorrect operation on through faults, which are quivalent to steady-state conditions even though the currents ay be many times normal. The situations discussed by Mr. yrne are easily dealt with, provided that the designer is given l the necessary information.

I am interested in Mr. Howarth's remarks. The magnetizing rve is not linear anywhere, but if the flux density in one core raised, and in another lowered by the same amount, the sum their magnetizing currents changes very little. I cannot see ow a summation transformer can ever be considered to increase e overall accuracy, but its own error can easily be made very nall.

Mr. Sheppard was, I believe, the first person to explain to me ow summation circuits worked, and how "idle currents" npaired their performance. The same beliefs are still widely eld both here and abroad. My references were very carefully osen and discuss the subject adequately. High-reactance rrent transformers were used in Tables 2 and 3, and the ratio maximum to minimum flux densities was about 3 : 1.

In reply to Mr. Ashton, four 5 amp transformers in parallel ould presumably feed a 20 amp meter, which has nearly the me voltage drop and therefore imposes nearly four times as uch burden as a 5 amp one. The method of estimating the fective burden on paralleled transformers was specially chosen provide a ready formula for practical use.

Like Mr. Ashton I have met situations in which the power in e feeder has to be subtracted, and agree that the relevant rrent transformer often returns energy to the system. So far I know there is no simple method of overcoming the difficulty mentions in summing power at different line voltages.

Mr. Wilson's remarks are interesting. I should prefer burdens to be stated in ohms, since the active power and the voltage both vary with the load current. How to word the rating plates of summation transformers is often a problem, and I do not know of any standard method. When all the primary windings are equal we simply state "equal primary windings" and give the current rating of the coils. For unequal primary windings we give the ratio of each line transformer near the terminals of its appropriate primary winding. Many special cases arise which need a lot of thought.

There is no advantage in restricting the number of primaries, excepting the possible complication of having a large number of terminals. Ten primaries on one transformer are to be preferred in the case quoted by Mr. Wilson. The alternative means three summation transformers instead of one, three times the extra burden and twice the additional error.

Dr. Halacsy has probed more deeply into the effect of unequal turns compensation, and his conclusions form a useful addition to the paper.

As Mr. Vanderleck points out, no copper is saved by changing the point of paralleling, since the total cross-section must remain the same. He is also correct in saying that the overall error tends to decrease as the number of idle lines increases, although the difference is usually very small. I am interested in his method of measuring the current in a line connected to a busbar. If I have read correctly, the transformers carry equal but opposite currents when the line is disconnected, and the meter should read zero. In this case, and also when the line current is small, the method should still work quite well if the transformers are of the same design, since their errors should be nearly equal and therefore cancel out. Mr. Vanderleck's work on the change of ratio error with unequal transformers is interesting, and his Table A gives good confirmation of one of my conclusions under severe conditions.

In reply to Mr. Lancaster: I do not use turn compensation in summation current transformers, and the reasoning in the paper also applies to auto-wound units. Reverse currents were also mentioned by Mr. Ashton.

Cores which have been "permanently magnetized" soon become demagnetized when returned into service, by the normal

rise and fall of the current. Mumetal seems to be affected very little. With silicon irons, both of the grain-oriented and hot-rolled varieties, the performance may temporarily be worsened by up to 20%.

There is no doubt that the overall accuracy of a summation-transformer equipment is inherently as accurate, and very nearly as stable, as a single current transformer, and I cannot agree with Mr. Wollaston unless he is referring to power measurement in the same way as Mr. Stowell.

Mr. Stowell raises the question of a partially short-circuited turn on an idle line transformer. The additional error is not nearly so great as at first might be thought. In general it is negligible if the primary is earthed only at both ends. Should it be solidly short-circuited the leakage current is naturally greater, and the effect on the overall error might reach 0·5% in an unfavourable case. I agree that the introduction of a summ tion transformer makes no difference.

The point about relative burdens has already been dealt w The use of an auxiliary transformer to bring an odd ratio i line adds a considerable burden to that transformer. For li extra cost a summation transformer would make a cleaner and enable standard 5 amp instruments to be used.

I cannot agree with Mr. Stowell about Section 2.3. The fi paragraph states the old view and the second refutes it. T third is of relatively minor importance and explains the effect non-linearity in the cores. The fact that the total amount copper is not changed seemed too obvious for inclusion in paper, but as it is so, the burden on each transformer is the sa whether the parallel connection is made at the transformer o the meter terminals.

DISCUSSION ON "MEASUREMENT OF THE WINDING RESISTANCES OF A 132 kV POWER TRANSFORMER IN SERVICE"*

Before the North-Western Measurements Group *at* Manchester, 30*th March, the* North Midland Centre *at* Leeds, 16*th November*, 19 *the* Rugby Sub-Centre *at* Rugby, 2*nd February*, *and the* North-Eastern Radio and Measurements Group *at* Newcastle upon Ty 21*st February*, 1955.

Mr. R. Farrand (*at Manchester*): A method of winding-temperature measurement involving the use of d.c. injection is advantageous on two occasions.

First, during a heat test on site, it is often difficult to remove quickly the load from the transformer and transfer it to other sources of supply. Furthermore, owing to the necessary safety precautions, several minutes can elapse between complete shut-down and the receipt of authorization to work on the transformer on site. Hence the conventional method of winding-temperature measurement after shut-down is often difficult to apply and liable to large errors owing to the magnitude of the "shut-down correction."

The second case, as emphasized by the authors, is where the winding temperature is required under a cycle of applied load in order to study the thermal characteristics of the transformer. Here, a method of continuous winding-resistance measurement simplifies the performance of the test in that many shut-downs and restorations of load are avoided.

To make the authors' method more fully applicable, resistance measurements on delta windings require consideration. Would the authors comment on the methods they would adopt in such a case? Would they consider using a form of Faraday cage or a separation of the current- and voltage-measurement circuits?

Finally, I would like to raise a point concerning the loading of the transformer at Ironbridge. The setting and knowledge of the load is most important in a test of this nature, since the winding temperature must be related to a specific load. Would the authors comment on the method used for loading the transformer and indicate how the load was controlled?

Mr. H. W. Hardern (*at Manchester*): When determining the temperature rise of a transformer by classical methods, a substantial correction is required to allow for the temperature fall between the time of switching out and the time of obtaining a satisfactory resistance measurement. Bearing in mind this correction back to shut-down, it is a matter for considerable satisfaction that the authors, using the d.c. injection method of temperature measurement, have found such very good agreement with the other, and generally simpler, method of testing. Ho ever, we must not forget that both methods give only the avera temperature of the winding measured, and to arrive at temperature of the hottest spot, a further correction must added which can only be approximated to within a few degr centigrade. Consequently, I agree that, for general rout testing, the short-circuit method appears likely to be retained.

Prof. G. W. Carter (*at Leeds*): The authors imply that sensitivity of their method of measuring resistance was limi by the small direct current which had to be used in order prevent an undue increase in 50 c/s magnetizing current. T increase could be prevented if an equivalent, but opposite, dir current were passed through another winding.

The long time-constant for the distribution of direct curr between the three phases appears to be inconvenient wh measurements of the resistances of individual phases are ma but it is possible that it would exert only a second-order eff on readings taken for three phases in parallel. It would interesting to know whether this is so, and whether the auth consider that this is the reason for the more satisfactory resu obtained by a single shunt in the neutral. They might a consider modifying the time-constant by alterations which wo make no difference to the 50 c/s behaviour of the transform e.g. by increasing R_1 in Fig. 12(*b*).

The difficulty over the long time-constant, evident in variable apparent resistances shown in Fig. 11, could surely minimized by using data obtained from a succession of readi to eliminate the effect of inductance from the equation. Th if at three instants spaced by equal time intervals T the curre were i_1, i_2 and i_3, the equation

$$L\frac{di}{dt} + Ri = V$$

would approximately imply

$$L\left(\frac{i_2 - i_1}{T}\right) + R\left(\frac{i_2 + i_1}{2}\right) = V$$

$$L\left(\frac{i_3 - i_2}{T}\right) + R\left(\frac{i_3 + i_2}{2}\right) = V$$

* Wilkinson, K. J. R., and Harmer, J. D.: Paper No. 1626 M, January, 1954 (see 101, Part II, p. 308).

eliminating L we can deduce that the true resistance R is ven in terms of the three apparent resistances R_1, R_2 and R_3 by e equation

$$R = R_2\frac{(R_1R_2 + R_2R_3 - 2R_1R_3)}{R_2^2 - R_1R_3}$$

such a manner, it should be possible to approximate to the e resistance without waiting for steady conditions.

Mr. K. W. McBain (*at Rugby*): The excellent results of the ethod outlined by the authors were developed following some editable and valuable work which was carried out by the E.A. at Ironbridge substation on a 60 MVA 132/33 kV ON/OB nsformer during the years 1949–51.

The primary object of the initial tests was to ascertain actual nding temperatures under varying degrees of loading including ort-time overloads, and at the same time to check the perforance of the winding-temperature indicator. During these tests e resistances of the windings were measured after first disconcting the transformer from the supply as laid down in B.S. 171, d allowing a period of 4 min before the measurements were ken.

Coincident with these original tests by the B.E.A., the authors ere studying the general problem of measuring the resistance of nsformer windings while under normal excitation. Experiental work indicated that their method was a practical one, d it thus gave rise to the finalized tests which are referred to in e paper.

The authors have referred to similar measurements of winding sistance carried out on a transformer during a short-circuit at run in the factory on a 3-phase 120 MVA 275 kV transrmer. Transformers of much larger output are in demand all er the world. For example, in the home market serious nsideration is being given to the installation of generator nsformers having a 3-phase output of 210 MVA 275 kV, while the export market some users are considering installing 3-phase nks to give outputs as high as 450 MVA.

A short-circuit heat run in the factory on the 120 MVA 275 kV nsformer required approximately 28 MVA of test-plant achines, while an a.c. heat run at rated losses of, say, 1 200 kW a 210 MVA transformer would require approximately 66 MVA generating plant and 60 MVA of test-plant transformers. It ll thus be appreciated that, for the larger sizes of transformers, nsideration has to be given to heat runs in the factory using rect current and not alternating current. Therefore, while e authors mention having to inject direct current of 3·4 amp in ch of the three phases we visualize that, for d.c. heat runs on e larger sizes of transformers, the test engineer will have to ve available in the very near future direct currents of up to 000 amp.

Mr. T. H. Milne (*at Newcastle upon Tyne*): In the past, the rmula given in B.S. 171 for the temperature drop in the first ur minutes of cooling has been extremely useful, and it is atifying to find the rule substantiated in this way. About hteen months ago I was associated with the commissioning of 60 MVA transformer which had stood idle for some time. on-standard coolers were fitted, and a short-circuit heat run as organized to establish the overall capability. During the at run, temperatures were measured at many points until a eady condition was reached. After shut-down, and in the sence of a highly-organized technique for obtaining the nding resistance within four minutes, the first reading was tained after about ten minutes, and readings were continued r half an hour. In spite of the gap of six minutes it was found at the curve from the British Standard formula, when started om 78° C, joined up smoothly with the measured values, but plotted from 2° C on either side of this starting-point the curves were not continuous. Thus the accuracy was assessed at not better than ±1 or 1½° C in this instance. Other constructional methods were tried, but their accuracy, in the circumstances, was considered to be even poorer.

The B.S. 171 formula is a little odd, as a plot of the differences from Table 12 will reveal. It is interesting to speculate on the reasons for this, and to observe that Fig. 9 of the paper would suggest a slightly smoother set of values to be appropriate.

Mr. I. R. Neill (*at Newcastle upon Tyne*): With the increase in ratings and voltages the rapid measurement of resistance of the windings at the conclusion of heat runs is becoming more difficult, and corrections for cooling of the winding by 7 or 8° C are sometimes necessary.

The possibility of taking continuous readings during short-circuit tests is very attractive, and this application of the superposition method appears to be the most valuable. The resistance measurement while in service can only be done on comparatively few transformers, and under these conditions the authors' curves of winding temperature against time show that the hot-spot indicator can be relied on to follow winding-temperature changes accurately. Reliable test measurements on which to base the calibration of the indicator are the main requirement. If the superposition method is to have a wide application, the resistance of delta-connected windings will have to be measured. Has a method of doing this been devised for a transformer on short-circuit test?

When the site tests were carried out on the 132 kV transformer, resistance readings were taken on each phase as well as with the neutral shunt. No mention is made of any difficulty in measuring the resistance of the individual phases due to transient unbalance of the currents. Is this a peculiarity of the 5-limb core construction which does not appear in transformers with 3-limb cores?

Mr. B. E. Western (*at Newcastle upon Tyne*): Only by methods of measurement which do not disturb the operation of the transformer is it possible to obtain exact information of the temperature under operating conditions and of the thermal time-constants, which is necessary if thermal image devices are to be calibrated correctly and used with confidence.

The method of measuring the winding resistance described by the authors was necessarily complicated and expensive because of the conditions under which the measurements were made. In works tests where conditions are more stable and more easily controlled, very accurate measurements of winding resistance can be made while the transformer is carrying load current, with much simpler equipment.

I made some tests on comparatively small transformers during short-circuit heat runs, using a superposition method similar to that of Messrs. Lockie and Stein referred to by the authors. The method consists in principle of arranging the secondary connections of the transformer so that during a short-circuit the measuring equipment which employs direct current can remain connected to two points on the secondary winding which are at the same potential so far as the alternating current is concerned. One test was on a 150 kVA 3-phase transformer whose primary windings were excited in series from a single-phase supply. The resistance of two of the secondary phases in parallel was measured with a Kelvin double bridge. A simple filter consisting of inductance and capacitance was used to prevent any residual alternating current from flowing in the galvanometer.

The results are shown in Fig. C. The oil temperatures were measured by means of thermocouples. The important feature of the method was the high degree of "definition" obtainable; the temperature could be followed very closely during any part of the test.

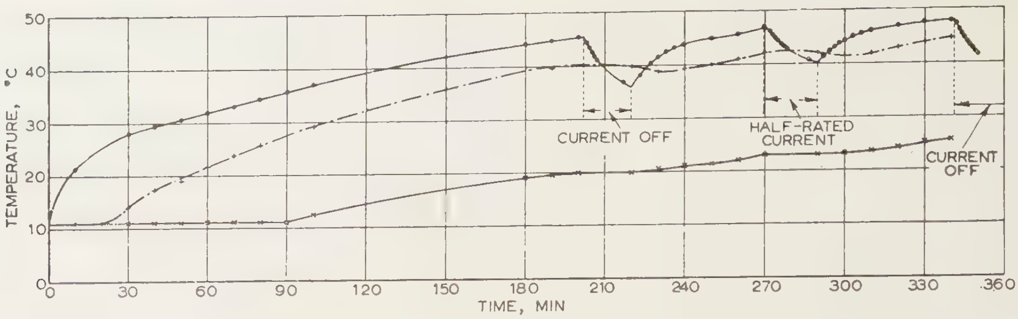


Fig. C

○———○ Winding temperature by resistance.
· — · — · Top-oil temperature.
× ——— × Bottom-oil temperature.

Dr. K. J. R. Wilkinson and **Mr. J. D. Harmer** (*in reply*): Messrs. Farrand and Neill refer to the measurement of windings which are delta connected. If a transformer is on short-circuit test the measurement of its delta resistances by injection can be similar to the method used for a star winding, but if the delta windings are to be measured by injection when the transformer is in service, it would be appropriate to feed direct current at one corner of the delta and provide shunts in each phase. Comparison of voltage and current could be achieved by a bridge method, using appropriate filter systems. If it were not possible to test with one terminal of the delta earthed, it would be necessary to work at the potential of the current-injection corner.

In the tests at Ironbridge it was, of course, not power but transformer load current which required control; this was achieved by exciting the transformer from its own generator, and the operation included varying the generator voltage so as to circulate reactive power.

Prof. Carter and Mr. Neill refer to the long time-constant which governs the distribution of direct current between phases, as shown by our measurements on a transformer undergoing a short-circuit heat test. It is unlikely that this time variation in distribution played any significant part at Ironbridge, because in those tests the injected current was maintained constant not only throughout the tests but for a sufficient time before readin were recorded. In our opinion the more satisfactory nature the results obtained when measuring three phases in paral suggests that the small system disturbances, which are manif as fluctuations in each phase, are due to changes in symmetri load, which thus cancel in their effect at the neutral.

Prof. Carter offers an expression by which the (assum constant) resistance of a winding could be determined in spite a long-term current change delayed by inductance. Unfor nately, in the transformer to which Fig. 11 applies the expressi could only apply to a thermally steady condition, since t thermal and (relevant) inductive time-constants of that trar former have comparable orders of magnitude.

Mr. Milne draws attention to the failure of the points defin in Table 12 of B.S. 171 to lie on a plausible curve. It is c opinion that the factor of 0·5 in that Table (corresponding 4 min) is about 10% low.

Mr. Western infers that simpler injection-testing equipme can be used in a factory because conditions there are mo stable and more easily controlled than when a transformer is service. It is not only, of course, the greater stability or ease control, but mainly the fact that the transformer can be tested short-circuit, which simplifies such tests.

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Paper No. 1847 S
Oct. 1955

DYNAMIC OPERATION OF AN A.C. NETWORK ANALYSER

By S. KANEFF, B.E.

(*The paper was first received* 26*th October*, 1954, *and in revised form* 1*st February* 1955.)

SUMMARY

Methods are described for representing synchronous machines, by eans of which an a.c. network analyser can be constructed to solve oth steady-state and transient power-system problems automatically, thout the need for tedious step-by-step processes. An existing c. network analyser may readily be converted to dynamic operation modification of the generator units only, as herein lies the only dical alteration in representation proposed. Choice of time scale r the study of electro-mechanical transients is arbitrary. However, vantages are indicated for a time scale of the order of 1 min on the alyser corresponding to 1 sec on the actual power system. Results tests (employing a.c. network analyser units) are included, and ssible improvements are discussed.

LIST OF SYMBOLS

P = Synchronous machine rating, kVA.
P_a = Power (watts) representing 1 per-unit power on the network analyser.
P_d = Synchronous-machine damping coefficient.
P_e = Electrical output power.
P_{in} = Mechanical power input to nth machine.
P_m = Power supplied by prime mover.
$P_{0s}(\delta)$ = Synchronous power output.
P_s = Power flow causing energy to be stored in, or taken from, synchronous-machine energy store.
P_u = Per-unit rating of synchronous machine.
f_a = Analyser-network operating frequency, c/s.
f_e = Frequency in true time represented by 1 volt of energy-store output signal, c/s.
f_i = Instantaneous frequency of actual synchronous machine.
f_{im} = Instantaneous frequency of synchronous-machine model.
H = Stored-energy constant, kWs/kVA.
M = Inertia constant = $PH/180f_i$.
$t = \dfrac{\text{Actual analyser time}}{\text{True time represented}}$ = Time lengthening factor.
k = Velodyne gearbox speed-reduction factor.
R = Velodyne sensitivity, r.p.m./volt.
r_h = H-set resistance across which input to energy-store current amplifier (Fig. 2) is developed, ohms.
r_1 = H-set resistor (see Fig. 5).
ϕ = Phase displacement of machine-model phase adjuster from its steady-state position.
δ = Angular displacement between machine internal voltage and some fixed reference.
T = Wattmeter reference torque.
V_c = Voltage across energy-store condenser.
V_{cs} = Steady-state voltage across energy store, producing current i_v in wattmeter element (b), potential coil.
W = Energy of energy-store condenser at voltage V_{cs}, watt-seconds.
G = Ratio of current output to voltage input for energy-store current amplifier.
i_c = Instantaneous current in wattmeter element (b), current coil, which, together with the instantaneous current i_v in element (b), potential coil, produces torque T (Fig. 2), amp.
i_d = Instantaneous total current in wattmeter element (b), potential coil for Fig. 5.
i_t = Instantaneous total current in wattmeter element (b), current coil for Fig. 5.
v_d = Instantaneous tacho-generator output voltage (see Fig. 5).
I = Moment of inertia of rotors of actual synchronous machine.
ω_i = Total instantaneous angular velocity of actual synchronous machine.
ω_n = Normal steady-state angular velocity of actual synchronous machine.

(1) INTRODUCTION

In a previous paper,[1] methods were given for the representation of synchronous machines using high-frequency techniques, and it was mentioned that the same basic principles could be applied at much lower frequencies, e.g. 50 c/s.

The original 10 kc/s system, although satisfactory in operation, is considered needlessly complicated, and the advantage of repetitive operation is unnecessary, especially as its elimination results in considerable circuit simplification.

Subsequent work has led to the development of an electronic-electro-mechanical combination using the same principles of operation as previously, but much simpler in detail. The method can enable an existing a.c. network analyser to be converted to dynamic operation by modification of the generator units only.

The method proposed can be used independently of the analyser frequency of operation. The choice of a time scale for the solution of power-system electro-mechanical transients is arbitrary, but a time scale of the order of 1 min on the analyser to represent 1 sec on the actual power system commends itself for the following reasons:

(*a*) Direct pen recording of results, such as swing curves, is readily possible.
(*b*) Ordinary relays or suitable mechanical switching can be used for problems requiring switching operations.
(*c*) Design of equipment is simplified.
(*d*) The waiting time for the tracing of swing curves is still not disagreeably long.

The representation of a power system is to be the same as that used in the a.c. network analyser except for the representation of synchronous machines, which are consequently the only units discussed. The prototype representation used readily available components, and, as a result, was more complicated than necessary. It is indicated, however, how a very much simplified version of the method is obtained.

(2) SYNCHRONOUS-MACHINE REPRESENTATION

The representation of a synchronous machine to be discussed is based on the phase-modulation method,[1] the schematic of which is shown in Fig. 1.

ritten contributions on papers published without being read at meetings are ed for consideration with a view to publication.
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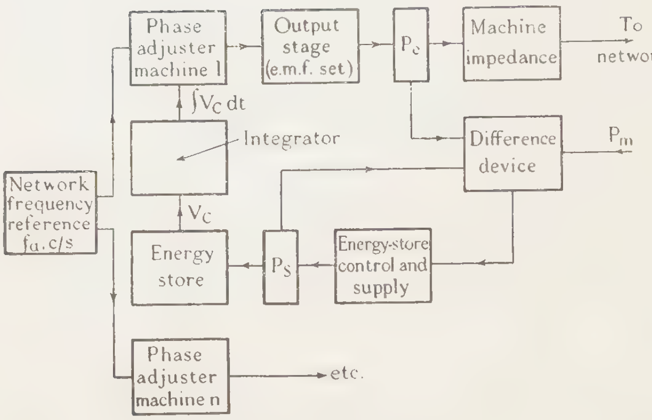

Fig. 1.—Basic phase-modulation system for synchronous-machine representation.

(2.1) Functional Operation

The following relations are satisfied in a synchronous machine at every instant of time:

Power supplied by prime mover = (Electrical output power) + (Power flow being stored in, or taken from, machine rotors) . . (1)

$$\text{Total energy stored in rotors} \propto \left[\text{Instantaneous}\begin{Bmatrix}\text{speed}\\ \text{frequency}\end{Bmatrix}\right]^2 \quad . \; . \; . \; (2)$$

The aim of Fig. 1 is to make relations (1) and (2) apply at all times, and it operates as follows:

An a.c. supply of frequency f_a cycles per second provides power for the model power-system network.

Setting the phase adjusters of each synchronous machine unit, and thus adjusting the phase of the output-stage voltage (representing synchronous-machine internal voltage) relative to a fixed reference, is clearly one of the factors controlling power-flow conditions in the model power-system network (as in the a.c. network analyser). Machine internal impedance is added after the output stage.

The wattmeter P_e measures the power flow from the machine model to the network, and this reading is compared with a reference power input P_m representing the prime-mover output power. Any difference between P_m and P_e is used to control the flow of energy to or from an energy store which can be conveniently, but not necessarily, a condenser, representing the energy stored in the rotors of the actual synchronous machine. Different inertia constants are obtained by changing the "effective" size of the energy store. The wattmeter P_s measures the power flow to or from the energy store, and the readings of P_s, P_e, and P_m are compared in the difference device in such a manner that if relation (1),

i.e. $$P_m = P_e + P_s \quad . \; . \; . \; . \; . \; . \; (1a)$$

does not hold exactly, a signal is obtained which adjusts the energy-store control and supply in such a manner that the equality is restored.

Then, assuming that P_m has been preset to some value, the model behaves in such a manner that the relations (1) and (1a) always apply. The result of this action is that, at all instants the energy store holds the correct amount of energy corresponding to that actually stored in the rotors of a synchronous machine that is being represented, operating under the same conditions.

Because in a condenser the stored energy is proportional to the square of the voltage across the condenser, and comparing this with relation (2), it is seen that if the analogy

Instantaneous frequency, f_i, of actual synchronous machine $\equiv$ Voltage, V_c, across condenser . . . .

is used, relation (2) will also be satisfied for the machine model by making

Instantaneous frequency of machine model, $f_{im} \equiv$ Voltage across condenser, V_c.

(Owing to frequency scaling, f_i is not necessarily equal to f_{im}.)

Because the instantaneous frequency equals the rate of change of phase, the phase adjuster must be controlled so that

$$\text{Phase angle, } \phi = \int V_c dt$$

Thus relations (1), (1a) and (2) can be satisfied at all times.

It is only the phase and frequency excursions from normal steady-state conditions that need be represented in the abo circuit operation, so that, during steady-state conditions, t stored energy is constant, the phase adjusters are stationary the phase setting to give required steady-state power flow, a no signal comes from the energy store. These conditions repr sent the actual power system operating at its normal steady-sta frequency. However, this latter frequency need have no dire relation to the model-network-analyser operating frequency, which may, depending on design, have a value somewhere in t range 50c/s–10kc/s.

During disturbance conditions, when $P_s \neq 0$, stored energy not constant with time, and phase-angle swings occur on t system. It is convenient to employ a lengthened time scale represent the power-system electro-mechanical transients, si this simplifies design as well as being convenient for obtaini results. For example, if t seconds on the model represent 1 s on the actual power system, for a swing curve which has a peri of the order of 1 sec in true time, the phase adjuster of t machine model is required to be moved only at the rate 1 cycle in t seconds—a much easier task because the pha adjuster is intended to be itself an electro-mechanical devi possessing inertia.

The problem of design of units is thus simplified by lengtheni the time scale to represent electro-mechanical transients. At t same time, recording of results can be by pen recorder a complex switching functions can be performed simply by rel or mechanical devices.

It is apparent that the position of the energy store in t representation of Fig. 1 is not exactly similar to the case o synchronous machine, because energy does not actually fl between the model network and the energy store as it can do the actual case. However, the action in making relations and (2) hold good results in the same overall operation of t model compared with the actual synchronous machine, and this respect the behaviour of the condenser energy store analogous to that of the rotors of a synchronous machine.

An important feature of the method of representation bei presented concerns the behaviour during transient disturbanc Consider the normal differential equation for the nth mach on an n-machine system:

$$M_n\frac{d^2\delta_n}{dt^2} + P_{dn1}\frac{d(\delta_n - \delta_1)}{dt} + P_{dn2}\frac{d(\delta_n - \delta_2)}{dt} + \ldots + P_{0sn}[(\delta_n - \delta_1)(\delta_n - \delta_2)(\ldots] = P_{in} \quad .$$

(Subscripts 1, 2, ... n, refer to the first, second, ... machines respectively.)

It will be recalled that, in eqn. (4), because the inertia consta

$_n$, depends on machine operating frequency, during transient sturbance conditions when, in general, the instantaneous achine frequency is varying, M_n will also be a variable. However, normal a.c. network-analyser studies ignore such variations d are based on constant speed of machine during transient sturbances, which results in computing inaccuracy.

(2.2) Units Employed

There are many possible ways in which the functional requirements of Fig. 1 may be realized—such methods may be purely electronic, electro-mechanical, or some combination of the two. Fig. 2 shows the functional arrangement of prototype equip-

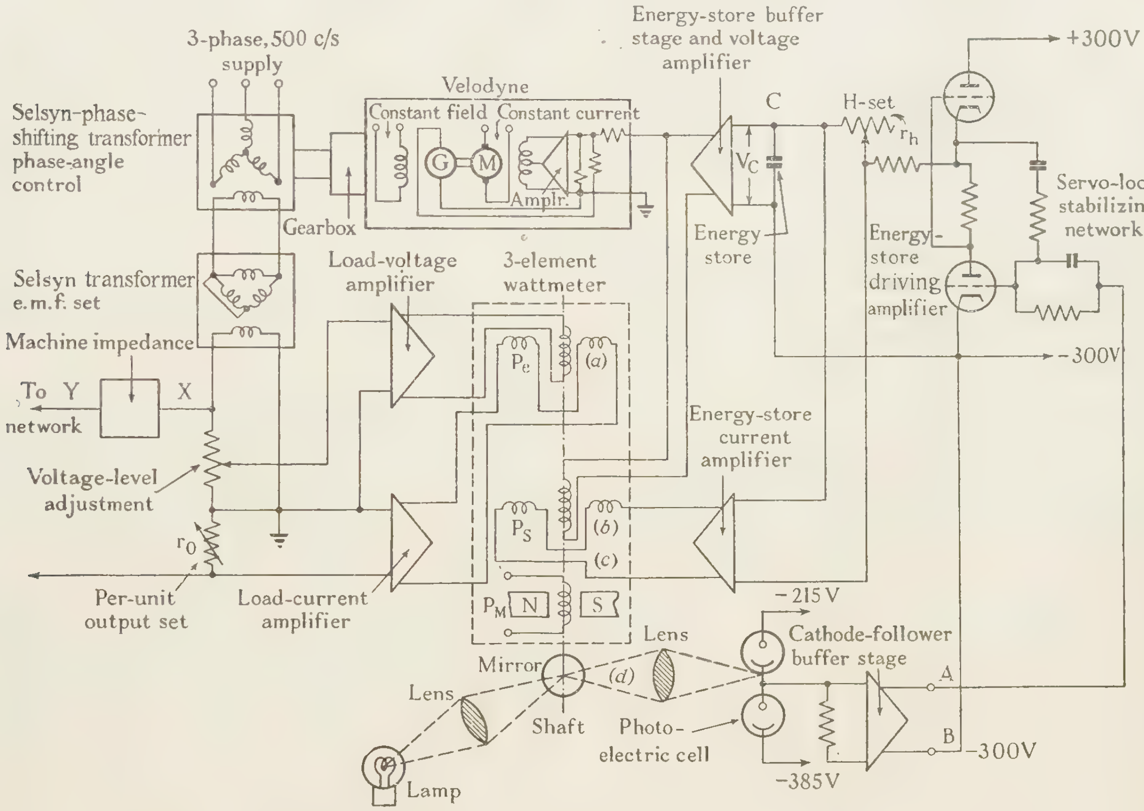

Fig. 2.—Units employed in synchronous-machine representation.

In addition to normal a.c. network-analyser studies, it is clear at any method of synchronous-machine representation which pends on a direct double-integration of eqn. (4) without taking o account the variation in inertia "constant" is also basically ccurate in this respect.

It is to be noted that the method of synchronous-machine presentation of Fig. 1 is not based on constant speed of machine ring transient disturbances—the analogy between stored ergy in the energy-store condenser and stored energy in the chine rotors, and consequently between voltage across the ergy-store condenser and therefore instantaneous machine presentation frequency and actual synchronous-machine tantaneous frequency, is exact. Accordingly, effects of viations from normal of the instantaneous frequency are rectly represented, which results in a fundamentally accurate thod of representation. As a consequence, a synchronous-chine model is obtained which behaves like the actual case for nsiderable departures of operating frequency from normal, s permitting accurate study not only of normal transient turbances but also of many asynchronous phenomena (e.g. behaviour of synchronous machines which have fallen out step) and the process of synchronization of machines. The quency range over which the representation behaves like the ual synchronous machine is limited only by the requirement t relations (1), (2) and (3) must hold good.

ment for converting an existing a.c. network analyser for dynamic operation. The details of the system were influenced by the fact that the analyser already employed two Selsyn transformers, one for phase-angle and the other for voltage-magnitude control, in each generator unit; consequently, these were directly incorporated in the design.

The representation employs a special 3-element wattmeter, developed for the purpose, with the following elements mounted on the one shaft:

(*a*) A normal dynamometer wattmeter for measuring power flow between the synchronous-machine model and analyser network.
(*b*) Another normal-type dynamometer wattmeter for measuring power flow to or from the energy store.
(*c*) A coil working in a permanent-magnet flux, for representing prime-mover mechanical output.
(*d*) A mirror for "zeroing" the wattmeter shaft by the use of photo-electric cells and electronic methods.

The energization requirements of the above elements are considerably less than for usual wattmeter elements in order to enable low-power electronic units to be used.

The operation is as follows:

Prime-mover output is represented by a torque on the wattmeter shaft, produced by a direct current flowing in the coil of element (*c*). During steady-state conditions, this torque is just balanced by an equal and opposite torque from element (*a*), which measures the electrical power flow between the machine model

and network. An optical system throws a beam of light on to the mirror on the wattmeter shaft, which reflects the beam on to two photo-electric cells arranged so that, if they receive equal illuminations, there is zero output from the circuit, while if there is unequal illumination a signal, whose polarity depends on which cell has the greater illumination, is obtained across AB. This signal is adjusted to zero when the wattmeter shaft is in its zero position, and accordingly any movement of the wattmeter shaft from the zero position causes a signal at AB of polarity depending on which side of zero the wattmeter shaft occupies.

At torque balance, with the signal at AB zero, the energy-store driving amplifier is adjusted so that the potential at C is then zero relative to the ± 300 volt supply—i.e. the voltage across energy-store condenser is 300 volts. This condition applies to steady-state operation, and the analogy 300 volts $\equiv$ 50c/s is then used for subsequent instantaneous frequency control.

During disturbance conditions, if instantaneously $P_e \neq P_m$, there is a torque unbalance on the wattmeter shaft which produces a signal of a particular polarity at AB; this results in energy flow in the energy-store circuit which is metered by the element (*b*), and the flow is in such a direction that it provides a torque on the wattmeter shaft acting to restore torque balance, the connections being such that relation (1*a*) applies. The voltage across the energy store then changes with time, and this signal is used to control the instantaneous machine frequency.

The identity (1*a*) can readily be maintained to the degree of accuracy required by provision that the gain round the subsidiary loop consisting of the wattmeter, photo-electric circuit, energy-store driving amplifier and energy-store metering amplifier is sufficiently high. [It will be realized that the purpose of the four amplifiers supplying elements (*a*) and (*b*) is to prevent the wattmeter from unduly loading the circuits concerned. However, as discussed later, by suitable circuit rearrangement these amplifiers can be dispensed with.] The subsidiary loop requires stabilizing, as otherwise it is subject to self-oscillation, for which purpose the network on the input side of the energy-store driving amplifier is used. Thus the required signal at AB to maintain given power-flow conditions to or from the energy store can be obtained from an extremely small "off-zero" movement of the wattmeter shaft, this movement being entirely negligible with sufficiently high subsidiary-loop gain.

With regard to the phase-angle control section, it is seen that the Selsyn transformer which sets the phase relation between the machine e.m.f. and the rest of the system network is shaft-coupled through a gearbox to a velodyne unit.[2] The velodyne is an electro-mechanical device in which the output-shaft speed is directly proportional to an input voltage signal—consequently when the voltage across the energy store (with a suitable buffer stage) is applied as an input to the velodyne, the total angular movement of the velodyne shaft depends on the time integral of the signal across the energy store, so that the velodyne performs the integration function required in Fig. 1. In addition, it mechanically drives the Selsyn-transformer shaft to the required angular position at every instant. The gearbox allows high-sensitivity operation, i.e. (high speed of rotation of the output shaft)/(voltage input signal) of the velodyne, which thus improves overall accuracy.

The relation between velodyne sensitivity and gearbox ratio is as follows:

Required speed of Selsyn transformer shaft for a Velodyne input signal of 1 volt is

$$\frac{f_e}{t} \text{ revolutions per second} = \frac{60 f_e}{t} \text{ revolutions per minute}$$

so that

$$\frac{R}{k} = \frac{60 f_e}{t}$$

or

$$k = \frac{Rt}{60 f_e}$$

For example, if 300 volts $\equiv$ 50c/s,
$R = 50$ r.p.m./volt,
$t = 50$ times,

then the gearbox reduction k is 250.

As mentioned previously, only the variations about the norm[al] operating frequency are of interest, so that when the volt[age] across the energy store is 300 volts, which is equivalent to 50[c/s], the system is operating under steady-state conditions and [the] Selsyn-transformer shaft must be stationary. Only chan[ges] above and below the condenser voltage $V_c = 300$ volts result [in] moving the Selsyn-transformer shaft—this is obtained [by] applying the input signal to the velodyne relative to zero volt[age] on the system, i.e. when $V_c = 300$ volts the velodyne in[put] signal voltage is zero.

(2.3) Behaviour of the Synchronous-Machine Model

The behaviour of the representation under various conditi[ons] is considered.

(2.3.1) Single Synchronous Machine.

When the synchronous-machine model is working alone, [i.e.] no connection is made to the rest of the model analyser netwo[rk], P_e equals zero of necessity, so that P_m must also equal ze[ro], otherwise there is a torque unbalance on the wattmeter sh[aft] which must be counteracted by energy flow P_s, which results [in] the machine accelerating or decelerating.

Then with $P_m = 0$ and $V_c = 300$ volts, the machine mo[del] operates in a manner similar to a synchronous machine be[ing] driven at synchronous speed by its prime mover but not co[n]nected to its power system. The power supplied by the pr[ime] mover is just sufficient to overcome all losses. In the actual ca[se] the power balance cannot be maintained exactly for an indefi[nite] time owing to changing losses and input, so that the speed [will] not be constant but, owing to automatic governor action, [will] vary about the speed at which the governors are set.

In the simple synchronous-machine model, however, beca[use] there is no automatic governor control (although this may [be] added as discussed later), any slight changes in parameters [due] to heating and other effects with time tend to cause drift in [the] subsidiary loop. Although the magnitude of such drifts [is] reduced by the factor of the subsidiary-loop gain, they are [not] corrected entirely (for which purpose the gain would need to [be] infinite), so that there is a small resulting variation in the volt[age] across the energy store which, over a period of several minu[tes], may result in a significant change in the speed of the synchrono[us] machine model.

In general, a single synchronous machine working alone i[s of] little interest in power-system investigations, but where suc[h a] study is necessary, governor action should preferably be inclu[ded]. Alternatively, the difficulty can be readily overcome by "[dis]charging" any drift signal when necessary.

(2.3.2) Synchronous Machine on Power System.

With a synchronous-machine representation connected to [the] analyser network, the above-mentioned drift is further drastic[ally] reduced in significance because any change in energy-s[tore] voltage due to this drift results, through the velodyne, in a cha[nge] in the phase angle of the Selsyn transformer. This in [turn] changes P_e, which thus produces torque unbalance on the w[att]meter shaft and thereby causes a compensating torque due t[o P_s] which results from an energy-store signal automatically in s[uch] a direction that it reduces the amount of drift, by the actio[n of] the main loop, consisting of the Velodyne Selsyn transfor[mer]

ttmeter, photo-electric circuit and energy store. The overall sult is that when the machine is working on its model system, e above-mentioned drift effects can readily be made negligible.

If there is no effective damping round the main loop, once ere has been a disturbance on the system which causes oscilla-ns in phase angle, these oscillations can continue with constant nplitude indefinitely, corresponding to an actual synchronous achine with no electrodynamic damping (i.e. no damping ndings or paths in which damping currents can flow due to cillations between stator and rotor fields). Such a synchro-us-machine representation gives a solution corresponding to at of an a.c. network-analyser study in which electrodynamic mping is neglected. The continuous constant-amplitude oscil-ions when subjected to a disturbance is the normal response of ossless double-integration system. The synchronous-machine presentation accomplishes a double integration as an overall sult, but without the use of simple integrator stages as such. us this overcomes some of the difficulties associated with the ter.

When connected to a model network subject to disturbance nditions, the synchronous-machine representation behaves as lows:

Suppose that initially the machine is delivering power P_e to e network which just balances P_m, the mechanical input, then der steady-state conditions $P_s = 0$ and the velodyne is tionary. If, owing to a disturbance, the machine output is ddenly reduced, there is a momentary torque unbalance on e wattmeter shaft and energy begins to flow into the store. is restores balance and causes the energy-store voltage to part from its steady-state value—relation (1*a*) applies in the bsidiary loop. The energy-store signal causes the velodyne to ve the Selsyn transformer ahead in phase—relations (1), (1*a*) d (2) apply at all times—so that the phase-angle swings which low are the same as those for an actual synchronous machine ith no electrodynamic damping) subjected to the same dis-bance conditions.

The same synchronous-machine representation can behave ually well as a motor or generator without change in connec-ns, except that the mechanical reference torque on element (*c*) the wattmeter shaft with machine acting as a motor is in the posite direction to that with the machine acting as a generator. setting $P_m = 0$ the unit can represent a synchronous ndenser.

(2.4) Setting the Required Machine Parameters

The following methods for setting the synchronous-machine nstants have been used in the present representation.

n order to maintain a high accuracy for all conditions of eration, a reference torque, T, is specified on the wattmeter ft, and operating conditions are adjusted so that the rated chine output, irrespective of its per-unit value on the system work, always produces a torque T from the wattmeter ele-nt (*a*). The torque T is chosen to be as high as possible, nsistent with the rating of the wattmeter elements.

The advantages of this arrangement include:

(*a*) The machine rating can be set by adjusting the effective gain f the machine-to-network metering amplifiers only.

(*b*) The prime-mover output can be set as a fraction of the rated utput; "full rating" requires the same current flowing through the oil of element (*c*) independent of the actual machine rating. This mplifies the addition of governor control. "Full machine rating" obtained when element (*c*) produces torque T.

(*c*) The energy-store circuit and setting of the H-factor become ndependent of the machine-rating setting. H is then set to its alue on the machine apparent-power base only, which is the figure ormally quoted for the machine, and need not be altered if the stem per-unit base is changed. The physical size of the energy ore is independent of the machine rating.

(2.4.1) Machine Rating.

Account must be taken of the fact that the network-analyser voltage may be stepped down in some problems to one-half or one-quarter of the normal, and even in these circumstances it is desirable to maintain the torque T on the wattmeter shaft for full machine rating so as not to lose accuracy in the subsidiary loop. Because the network current is reduced when the analyser voltage level is reduced, so also is the current output from the load-current amplifier, and in order to maintain the correct torque level it is convenient to increase correspondingly the output from the load-voltage amplifier by suitably adjusting its effective gain. This can be done automatically whenever the analyser voltage level is changed.

The machine rating can then be set by adjustment of the resistor r_0 (Fig. 2) across which the input signal for the load-current amplifier is obtained, and with the above arrangement this resistor can be calibrated directly in machine per-unit rating, which then holds good irrespective of the analyser operating-voltage level.

(2.4.2) Machine E.M.F.

The machine e.m.f. can be set by adjusting the Selsyn transformer (Fig. 2), which controls it in the same manner as originally intended.

(2.4.3) Machine Impedance.

Synchronous, transient, etc., impedance is included, as required, at the output of the e.m.f. set, i.e. at X in Fig. 2.

(2.4.4) Prime-Mover Power.

The prime-mover power is set by adjustment of the direct current in the coil of wattmeter element (*c*), as mentioned previously.

(2.4.5) *H*-Factor.

It is convenient to alter H merely by altering the effective gain of the amplifier which meters the energy-store current. This enables the energy store itself to be a condenser of fixed physical size. Care must be taken to ensure that over the possible range of values for H, and for the time scale involved, there is a significant current flow in this unit, otherwise the power flow becomes difficult to meter accurately. The condenser should accordingly be as large and as loss-free as possible.

If an exact equivalence is to be maintained in size of energy store and machine rating in the machine representation as in the actual synchronous machine, the size of the energy store must be P_uP_aH watt-seconds. However, this may be modified because the only requirement is that the overall action of the energy store as regards instantaneous frequency should be the same in both cases. If the size of the energy store is P_uP_aH watt-seconds and there is a sudden change of machine output from P_uP_a watts to zero, P_uP_a watts must instantaneously flow into the energy store if the representation is in true time, i.e. P_uP_a watts are stored in a store of capacity of P_uP_aH watt-seconds. However, if the actual energy store is W watt-seconds, W/H watts flowing into it produce the same voltage change at the energy-store-condenser terminals as in the former case because the ratio of energy being stored to the energy-store capacity is the same in both cases.

This results in the same change in instantaneous machine frequency, and it is therefore possible to make the store of W watt-seconds represent any machine H-factor correctly.

To calibrate r_h (Fig. 2) in terms of H:

For a sudden full-load change in machine output conditions, the power flow to the energy store for operation in true time is W/H watts, which must result in torque T from element (*b*).

For operation in extended time, the rate of energy flow to the

energy store must be slowed down in proportion to the lengthening of the time scale, because the same total energy must be stored, irrespective of the time scale.

Therefore, at the first instant after the disturbance, the current flow to the energy store is

$$\frac{W}{tHV_{cs}} \text{ amperes}$$

The input voltage required to the current amplifier is

$$\frac{i_c}{G}$$

Therefore $$r_h = \frac{i_c/G}{W/tHV_{cs}} = \frac{ti_cV_{cs}H}{WG} \text{ ohms} \quad . \quad . \quad . \quad . \quad (5)$$

Eqn. (5) gives the relation between the series resistance r_h and the H-factor, independent of the machine-rating setting.

There is no difficulty in providing sufficient variation in the above parameters to cope with all possible practical cases.

(2.5) Other Factors

In the above representation, there has been no inclusion of factors such as saturation, voltage-regulator and exciter action, governor action and electrodynamic damping, because the aim was to develop first the basic system. However, there is the possibility of representing all the above factors, working along the following lines:

Saturation.—By modification of machine impedance with time.

Voltage-Regulator and Exciter Action.—By controlling the machine e.m.f. with time.

Governor Action.—By controlling the current in element (c). This can be made to depend on the instantaneous machine frequency in order to simulate the correct governor characteristics.

Electrodynamic Damping.—In the actual synchronous machine, the damping action depends on the instantaneous angular-velocity difference between the stator and rotor fields. Because the absolute angular velocity not only of the rotor field but also of the stator field may, during transient disturbance conditions, be different from the normal steady-state value, the electromechanical damping to be represented in the synchronous-machine model must be dependent on the difference in the angular velocity of the two fields, as stated above, and not on the difference in angular velocity between the rotor field and some fixed reference such as the analyser network supply frequency of f_a. Electrodynamic damping can be introduced in the machine model by modification of the velodyne input signal in a manner which depends on the instantaneous difference in frequency between the Selsyn transformer shaft and the machine terminals at Y (which corresponds respectively to the rotor- and stator-field frequencies).

The slowed-down time scale facilitates the obtaining of time variation in the above quantities which could be made automatically dependent on the appropriate machine-model operating conditions.

(2.6) Setting the Analyser Network Power-Flow Conditions

In the normal a.c. network analyser, much time is usually spent in setting up the initial steady-state power-flow conditions prior to a system study. Using the dynamic synchronous-machine representation, this time can be greatly reduced, because in an n machine study ($n - 1$), machines can be set to give the required power-flow conditions. The final machine is then allowed to take up automatically the power flow required for steady-state operation of the system, if there is such a possibility. This is facilitated by the temporary introduction of heavy electrodynamic damping.

(3) PRACTICAL RESULTS

When initial tests to determine the practicability of the system were carried out, the special 3-element wattmeter required was not available (it was ready at a later date), so a single-element wattmeter was used, and the method of Fig. 2 was adapted accordingly. This involved using the wattmeter spring as the prime-mover reference torque, corresponding to P_m, and using the single dynamometer element to meter both power flows P and P_s. This was possible because the wattmeter current coil was in two sections, which were used respectively for metering machine-network current and energy-store current. The machine and energy-store voltages were both metered in the wattmeter potential coil by mixing the two signals in such a manner that they did not react on each other. This was accomplished by connecting the signals across opposite points in a Wheatstone bridge circuit—the wattmeter potential coil forming one arm of the bridge. Because the energy-store signals are, at most, only slowly varying direct current, while the machine-network signals are alternating current at the analyser frequency, in this case 500c/s, the two sets of signals meter separately.

Initially, two synchronous-machine models were constructed, the velodynes of each being shaft coupled (through gearboxes) to the existing analyser phase-angle Selsyn transformers.

A time scale of 50sec on the model was equivalent to 1sec in true time.

(3.1) Circuit Details and Performance

The arrangement of Fig. 2 was used. The basic circuit used for the four metering amplifiers is given in Fig. 3, direct coupling being used for simplicity and to provide the required frequency response. Amplifier characteristics are made almost independent of internal component variations by employing a large amount of negative feedback.

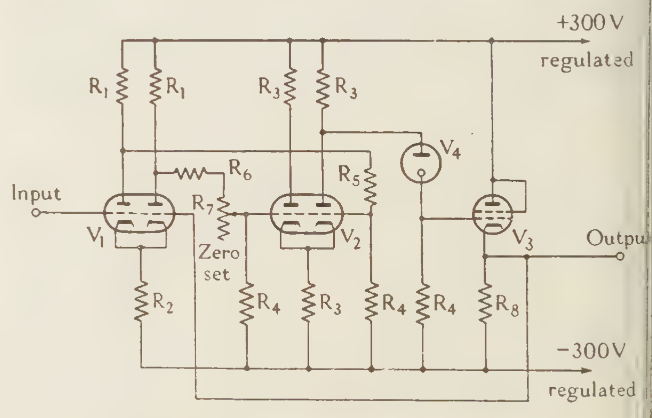

Fig. 3.—Basic metering-amplifier circuit.

R_1 = 220kΩ.
R_2 = 330kΩ.
R_3 = 100kΩ.
R_4 = 1·5MΩ.
R_5 = 526kΩ.
R_6 = 470kΩ.
R_7 = 100kΩ (rheostat).
R_8 is varied to suit the application.
V_4 = Miniature neon tube (for anode-grid coupling).

The circuit of Fig. 3 operates as follows:

With a positive-going signal on the input grid of V_1, the left-hand anode falls in potential while the right-hand anode rises. These changes are transferred to the grids of V_2 so that the left-hand anode of V_2 falls still further in potential, while the right-hand anode rises. Consequently, the grid of the cathode-follower output stage V_3, and therefore the cathode of the latter

ses in potential. This rise is applied to the right-hand grid f V_1, causing the left-hand anode of V_1 to rise in potential and ne right-hand anode to fall. The overall result of this action that the right-hand anode of V_1 acquires a potential very nearly qual to that of the input grid; there is just sufficient difference etween these signals, so that, when it is multiplied by the total ternal effective gain, it maintains the right-hand grid of V_1 at e particular potential conditions. For example, if the effective ternal gain is 2 000, the output follows the input signal to ithin one part in 2 000. If this internal gain is sufficiently gh, gain variations have little significance on the input/output lationship. If, in the above case, the gain falls to one-half of s original value, the output still follows the input to within ne part in 1 000.

In the circuit of Fig. 3 the overall voltage gain is unity, the utput stage being able to deliver several tens of milliamperes, nd the input impedance of the amplifier is considerably greater an 1 000 megohms, so that connection of the amplifier does ot affect circuit operation (this is especially important in the nergy-store metering). The unity-voltage-gain amplifier cannot e used for the machine-network current amplifier, where a latively high gain is required, because the series resistor r_0 Fig. 2) must not significantly affect network operation. There- ore, only a fraction of the output voltage is fed back to the put end. This secures the required gain.

Valves V_1 and V_2 are high-gain triodes, while V_3 is a beam trode in order to give the required output current, although in e special 3-element wattmeter system a lower-powered valve ffices for the latter.

Precautions must be taken to prevent metering errors due to e inductive nature of the wattmeter coils. This is accomplished adding sufficient resistance in series with these coils so as to ake the inductive reactance negligible at the frequencies of terest. The added resistance may be designed to be the nplifier internal resistance rather than a separate external sistor.

For all metering amplifiers, the input-voltage/output-current lationship was designed to have an accuracy of better than one rt in 500, the phase shift between input voltage and output rrent (in the wattmeter coil) being less than 0·1° up to 500c/s. ne d.c. drift of the output for an earthed input was in all cases ss than 0·0005 of the full output over a 30min period. Apart om a voltage-regulated power unit for the d.c. h.t. supply, and e type of feedback circuits used, no special measures were ken to minimize d.c. drift (a.c.-coupled amplifiers could equally ell have been used for the machine-network metering).

The energy store was a 10μF condenser, chosen for its tremely high insulation resistance and negligibly low dielectric sorption.

An important operating characteristic is the time delay between sudden disturbance on the model network and the initiation of rrect energy flow P_s to the energy store. This delay should as small as possible, but it must exist because of the inertia the wattmeter shaft as well as the electrical delays in the bsidiary loop. The measured delay between such a disturbance d correct energy-store operation was between 10–15 millisec, hich, because of the time scale used, is considered sufficiently nall. The constants of the subsidiary-loop stabilizing network ve a great influence on this delay time.

A further delay in the representation responding to a change of achine operating conditions is due to the fact that the velodyne tput shaft must lag slightly behind the input signal owing to e mechanical inertia of the velodyne rotor and the electrical lays in the associate circuits. With a sensitivity of 50 r.p.m./volt, e velodyne used in the tests accurately followed step inputs 1 volt with a total delay of approximately 15 millisec. Because the signal across the energy store does not change suddenly, but smoothly, and at a maximum rate of change corresponding to a frequency of about 1 cycle in 8 sec for the time scale used, the effective delay introduced by the velodyne is much less than 15 millisec.

The overall delay from initiation of a disturbance on the system to the start of correct Selsyn-transformer shaft motion is approximately 15–20 millisec, which is sufficiently small, even for the fastest electro-mechanical phase swings which, with the extended time scale, correspond to a maximum swing frequency of approximately 1 cycle in 8 sec. This delay can be improved for the 3-element wattmeter because of the higher torque/inertia ratio.

(3.2) Solution of Power-System Problems

The solution of a series of problems designed to test operation under various conditions was performed with the prototype models. Phase-angle swings could, if required, be recorded by means of a simple pen recorder mechanically coupled to the phase-angle Selsyn-transformer shaft. This method is simple, cheap and accurate.

As an example of the degree of accuracy obtained with the prototype equipment, Fig. 4 shows results of one of several

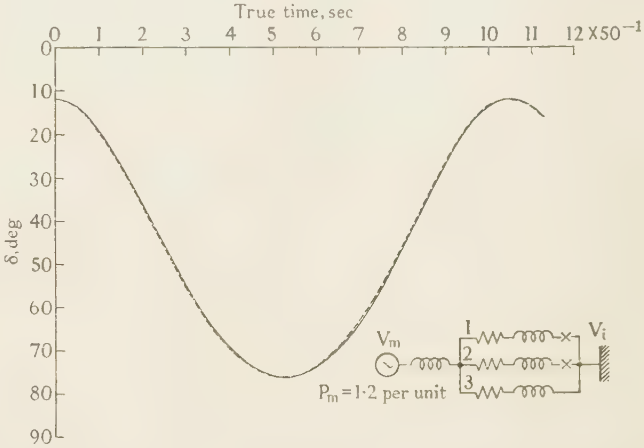

Fig. 4.—Swing curve for synchronous motor connected to infinite system.
——— Calculated.
------- Measured.

problems solved. The problem involves a synchronous motor of 1 per-unit rating on a 100 MVA base, with $H = 0 \cdot 2$, connected to an infinite system through three transmission lines.

Line Impedances.

Lines 1 and 2 in parallel $= 0 \cdot 0247 + j0 \cdot 1605$ per unit.
Line 3 (separately) $= 0 \cdot 0509 + j0 \cdot 318$ per unit.

Initial Conditions.

Synchronous-motor internal voltage V_m
$= \text{Infinite system voltage}, V_i$
$= 0 \cdot 8$ per unit.

Initial angle, $\delta = 12°$.
Mechanical power, $P_m = 1 \cdot 2$ per unit.

A disturbance results in the switching out of lines 1 and 2. The swing curve for this condition is required.

Model Network Details.

Base voltage: 50 volts $\equiv$ 1 per unit.
Base current: 50 mA $\equiv$ 1 per unit.
The 500 c/s mains supply was used as the infinite system.

Fig. 4 shows the measured result and compares it with the calculated curve.

Changing the value of H only had the correct effect of altering the swing time proportional to $\sqrt{H}$.

Results obtained with the experimental set-up for this and other problems could be made to agree with the calculated solutions to within 1%, while repeatability was better than 1%. The limit to accuracy was apparently controlled by the setting of initial conditions.

(4) DISCUSSION OF RESULTS

Results obtained with the synchronous-machine representation show good agreement with calculated values, even when the single-element wattmeter was used, before the availability of the special 3-element wattmeter. Although the set-up in terms of circuit components is complex, operation is simple and requires merely the setting of calibrated controls. Once the electronic circuits have been set up, they can, by virtue of the design, be operated for long periods without adjustment.

The results were obtained without the necessity of using a regulated supply for valve heaters, although the d.c. h.t. supply for the various amplifiers and energy store had to be voltage regulated.

The figure of 1% error attained seems, in some respects, better than necessary, and less accurate representation with the consequent simplification is suggested. However, in spite of the fact that power-system parameters are rarely known to such a degree of accuracy, it is at least of advantage to know that there is not a significant added source of inaccuracy introduced in the computations using these parameters.

The problem of simplicity in the synchronous-machine model has, however, been approached in a different manner, by modification of the representation without loss of accuracy, as described below.

It is readily apparent that the only limits on analyser-network operating frequency are those imposed by the 3-element wattmeter, so far as the synchronous-machine representation is concerned. Because the 3-element wattmeter can readily be constructed to give sufficient accuracy from direct current up to well over 2kc/s (and with special care up to 10kc/s), the same basic representation can be used for an analyser network operating anywhere in this frequency range, and indeed this system may be employed on analyser networks designed to operate over a wide band of frequencies, with no change in the basic machine representation.

(5) SIMPLIFIED SYNCHRONOUS-MACHINE REPRESENTATION

Since completion of the above experiments, effort has been directed towards a reduction of complexity without loss of accuracy or flexibility. This has resulted in the system of Fig. 5, which is again a direct application of Fig. 1, but it is considerably simplified as regards electronic components.

Although the Selsyn transformers of Fig. 2 have been retained in Fig. 5, other methods of obtaining phase-angle and voltage-magnitude control can be used. Units which are the same as in Fig. 2 are the 3-element wattmeter, in which the elements perform the same functions as before, and the photo-electric zeroing of the wattmeter shaft, in so far as a signal is obtained at AB (Fig. 5), which depends in polarity on which side of the zero the wattmeter shaft occupies.

The energy-store condenser and the four power-flow metering-amplifiers have been discarded.

For the purposes of metering power flow between machine and network, the potential coil of element (a) can be fed from straight across the line, as indicated. This does not upset the accuracy, because the connection as shown makes the poten[tial] coil indistinguishable from the analyser power supply, so far [as] the network and machine representation are concerned. T[his] could have been used in Fig. 2, except that, in the single-elem[ent] wattmeter, the voltage required to drive the appropriate curr[ent] through the voltage coil was greater than that convenien[tly] available.

The current coil of element (a) is fed from a variable-curr[ent] transformer, designed to have negligible effect on the netwo[rk]. This is possible because of the low energization requirements [of] the 3-element wattmeter. Phase shift produced by the induct[ive] nature of the potential and current coils can be readily correct[ed] if necessary.

The condenser energy store has been replaced effectively b[y a] fixed electro-mechanical store, i.e. the rotors of the d.c. mo[tor] and tacho-generator (which replace the normal velodyne [of] Fig. 2), together with gearbox and Selsyn rotor.

The total stored energy being represented is $\frac{1}{2}I\omega_i^2$.

The rate of energy storage is

$$\frac{d}{dt}(\tfrac{1}{2}I\omega_i^2) = I\omega_i\frac{d\omega_i}{dt} = I\omega_i\frac{d(\omega_i - \omega_n)}{dt}$$

The power flow to or from the energy store of the actual s[yn]chronous machine is then given by

$$I\omega_i\frac{d(\omega_i - \omega_n)}{dt} \quad . \quad . \quad . \quad . \quad . \quad .$$

The angular velocity of either the d.c. motor or Sels[yn] transformer shaft gives $(\omega_i - \omega_n)$ to the appropriate scale.

Therefore, if metering of the relevant stored energy for [the] model is required, it is necessary to have flowing in one coil [of] wattmeter element (b) a current

$$i_t \propto I\omega_i$$

while in the other coil a current

$$i_d \propto \frac{d(\omega_i - \omega_n)}{dt}$$

should flow. This ensures that the relation between sto[red] energy and instantaneous frequency is still correct, as in Fig[.] so that again the variable nature of the inertia constant [is] effectively taken into account. The output from the perman[ent]-magnet-field tacho-generator on the shaft of the d.c. motor gi[ves] a voltage $v_d \propto (\omega_i - \omega_n)$, so that a differentiator is required [to] produce a signal proportional to

$$\frac{d(\omega_i - \omega_n)}{dt}$$

A satisfactory electronic differentiator can be readily made [to] be inherently drift free, so that a current

$$i_d \propto \frac{dv_d}{dt} \propto \frac{d(\omega_i - \omega_n)}{dt}$$

is obtained in the potential coil of wattmeter element (b).

From the analogy, $V_{DC} \equiv 50$c/s, a current $i_t \propto I\omega_i$ can [be] obtained in wattmeter element (b) current coil by connecting [the] tacho-generator output in series with the regulated direct sup[ply] voltage, V_{DC}, as shown in Fig. 5, to obtain the correct depende[nce] on instantaneous frequency.

Amplifiers are not required for supplying wattmeter elem[ent] (b).

The machine H-factor is set by adjusting the value of i_t dur[ing] steady-state conditions, and the resistor r_1 (see Fig. 5) can [be] calibrated in terms of H. This setting is independent of

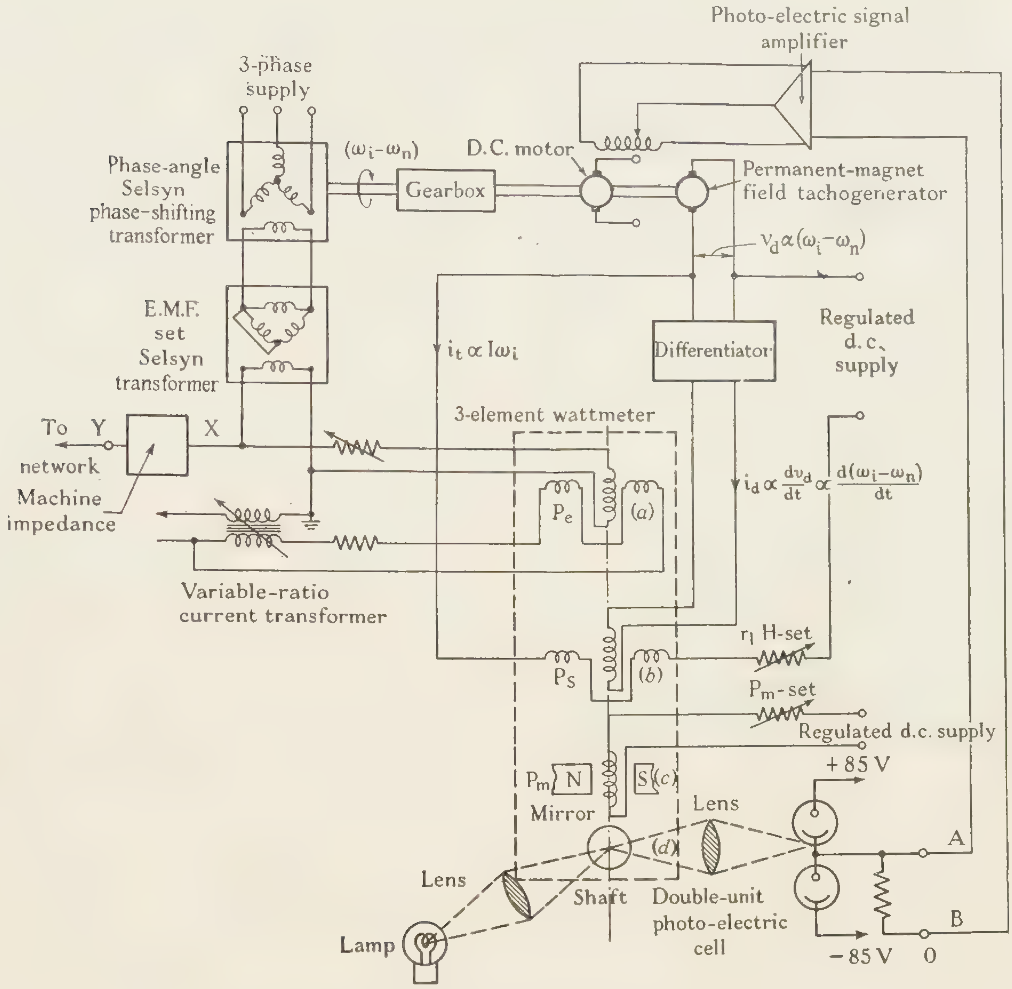

Fig. 5.—Simplified synchronous-machine representation.

achine-rating setting if the same philosophy of a reference attmeter torque, T, is used as previously, for Fig. 2.

Prime-mover power, machine rating and e.m.f. are set in the me manner as the methods used in Fig. 2.

The d.c.-motor tacho-generator unit is not used here as a ormal velodyne, which is essentially a device for producing an itput shaft speed proportional to an input-voltage signal. stead, no accurate velodyne circuit is required, because the attmeter, photo-electric cells, photo-electric amplifier, d.c. otor, tacho-generator and differentiator form a closed-loop stem which is itself self-correcting as regards drift and unlanced wattmeter torques. It results in a considerably lower herent drift than the system of Fig. 2, and faster response ne to disturbances, as well as satisfying relations (1), (1a) and satisfactorily.

The circuit of Fig. 5 operates as follows:

Suppose the unit is operating under steady-state conditions, in hich case the d.c. motor is stationary, $P_e = P_m$, and the tachoherator and differentiator give zero output. If P_e suddenly anges, the torque balance is upset, and a signal appears at AB, hich, suitably amplified, causes the d.c. motor to turn. This oduces a tacho-generator voltage proportional to the angular ocity of its shaft. This signal produces differentiator output rrent i_d in the wattmeter element (b) potential coil, which, gether with current i_t in the current coil, gives a torque correonding to P_s, the connections being such that relations (1) and (1a) apply. The d.c. motor shaft rotation is such as to make relation (2) also apply, if the analogy between voltage and frequency is used as above. With sufficient gain round the above loop, relations (1), (1a) and (2) apply as accurately as required.

The only accurate-in-itself electronic unit is the differentiator. The remaining circuit is of a "coarse" nature, the requirement being only that the gain should be sufficiently high. Apart from the d.c.-regulated power supply, the circuits can be realized with seven valves, including photo-electric cell. Supply to the d.c. motor and photo-electric amplifier may be from normal d.c. mains supply.

Initial tests have confirmed the practicability of the system.

(6) FURTHER WORK

Apart from development shown in Fig. 5, work is progressing in the representation of saturation, voltage-regulator and exciter action, governor action and electrodynamic damping, along the lines indicated in Section 2.5. It is hoped to present a report of these researches subsequently.

(7) CONCLUSIONS

(a) Methods for synchronous-machine representation presented enable a completely dynamic a.c. network analyser to be constructed. An existing analyser may be converted to dynamic

operation by the modification of generator units only. The methods may be used irrespective of the analyser frequency, and may be employed on an analyser network designed to work over a very wide network frequency range.

(*b*) The representation takes account of changes in instantaneous frequency of the machine during transient disturbances. The simulation is correct even when the machine speed has departed considerably from normal and may be used to study asynchronous phenomena accurately. In this respect the method is in advance of systems which do no more than speed up normal calculations but retain the usual assumptions employed therein.

(*c*) The representation can hold good both for steady-state and transient conditions.

(*d*) The setting of required power-flow conditions can be done automatically; and consequently a great deal of time is saved when setting initial conditions prior to a system study.

(*e*) A real possibility exists of simple representation of saturation, voltage-regulator and exciter action, governor action, electrodynamic damping.

(*f*) By suitable choice of time scale for electro-mechanical transients, switching problems and recording of results can be readily performed mechanically or electro-mechanically.

(*g*) Electro-mechanical devices are used in the representation wherever possible. Where electronic units have been necessary, overall performance has been made relatively independent of internal components by using feedback methods.

(*h*) A time scale of approximately 1 min on the model to represent 1 sec in true time is recommended for studying electro-mechanical power-system oscillations.

(*i*) Because of the speed of operation, the representa enables problems to be examined in more detail than hith This facilitates the improvement of power-system operation design.

(8) ACKNOWLEDGMENTS

The author wishes to thank the Directors of the Br Thomson-Houston Co., Ltd., for the opportunity of workin the initial prototype system in the Electronic Engineers' D Rugby, and later at Willesden. Acknowledgments are du Dr. J. R. Mortlock for initiating the work, and to Mr. L Ludbrook for assistance in servo stabilizing problems.

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DISCUSSION ON

"SERVICE EXPERIENCE OF THE EFFECT OF CORROSION ON STEEL-CORED ALUMINIUM OVERHEAD-LINE CONDUCTORS"*

Before the MERSEY AND NORTH WALES CENTRE *at* CHESTER 25*th October*, *the* IRISH BRANCH *at* DUBLIN 18*th November*, *and the* NORTH-EAS CENTRE *at* NEWCASTLE UPON TYNE 22*nd November*, 1954.

Mr. J. A. Spence (*at Chester*): In Section 2.1 it is stated that 12% deterioration in the strength of the conductor is allowed before renewal, which means about 30% reduction in the strength of the aluminium strands. I presume that this means about 30% reduction in the cross-sectional area of the strands. Does this mean that the maximum permissible loading of the conductor is thereby reduced? The maximum short-time rating of the $0\cdot175\,in^2$ conductor is about 700 amp, which is a very high ceiling. Surely 30% loss in the cross-sectional area would reduce this considerably.

In Section 2.2 mention is made of the measurement of the loss by the resistance of the composite conductor, and it is stated that it is not a very accurate way of carrying this out. I recall a case where the resistance of a conductor *in situ* was measured on one line. The resistance was much higher on one phase compared with the other two. Since it was not a very accurate method of measuring the loss on the cross-section, immediate action was not taken except to send a sample to the B.E.A. Laboratories. It was confirmed that the conductor should be changed as soon as possible, and the following week the conductor failed in t places.

In Section 6.1.1 mention is made of an accelerated test determining the behaviour of the grease in the conductor. W sort of tests are used to produce this acceleration? Are t any tests in which we can accelerate the corrosive attack on conductor to determine in a short time how various type conductor will behave?

In Sections 6.1.2–6.1.5 various types of greases are mentic and the limitations are quoted. I suggest that a silicone of grease, although expensive, may justify the cost invol since it may produce a longer life. If a grease is to extend life of a conductor by 10 years (I presume that is a fixed amo since the grease will not deteriorate according to the surroundi whether coastal, industrial or rural), surely all conductors sh be greased. If it is economic to extend the life of one condu by 10 years, it is economic to extend the life of another on 10 years. The cost of changing a conductor is by no m always apparent. I do not know whether the cost quoted by authors is only the cost of the conductor plus the labour, but if we consider that a line out of action may mean that r

* FORREST, J. S. and WARD, J. M.: Paper No. 1611S, January, 1954 (see **101**, Part II, p. 271).

efficient plant has to be shut down in favour of less efficient plant, it may cost £1 000 a week and should be considered in the costs of changing a conductor. For 275 kV lines which are capable of carrying 400–500 MW it would be many times that figure. Hence the cost of the conductor would be a great deal more than is apparent and as calculated in the paper. I therefore suggest that all conductors be greased throughout and overall. By doing so, even if it means an increased cost of the conductor and the labour, the actual cost and troubles involved would be well worth while in the long run.

Dr. H. E. Priston (*at Chester*): I am conscious of the necessity for improvements in the method of application of grease when the conductor is being manufactured, but it is necessary to examine first the desirable properties of the material required. There must be no direct corrosion by the protective material, excessive drainage at maximum sun temperatures must be resisted, removal by wind and weather should not take place and there must not be excessive deterioration owing to oxidation, so that there is no flaking or development of voids when strands of the conductor loosen in service. It seemed that the most profitable approach, based on earlier work, was to make the aluminium-base grease (mentioned in the paper) reversible. By this I mean that the grease should be capable of being heated to liquefaction and applied in that state by normal stranded-conductor production methods, and that it should, on cooling, revert approximately to its normal state. However, conventional aluminium soap greases, when heated to liquefaction, do not revert to their original state when cooled, but they exhibit somewhat crumbling jelly-like structures which possess very different properties from those of the original grease. The ideal of a reversible grease is not easy to achieve, but considerable success has now been obtained, and a grease is available which can be applied in the liquid form and a good protective coating on all parts of the conductor can be obtained. This material has been tried out extensively under practical stranded-conductor manufacturing conditions, and it has much better non-draining characteristics than petroleum jelly.

The use of such a material also overcomes some of the difficulties which have been advanced in the case of the black bitumen-base grease (*b*). This is a very effective protective, but application to the conductor is difficult, as it cannot be liquefied, and excessive quantities will tend to drain from the conductor as threads of grease, sometimes with unfortunate effects on anything beneath the conductor. The new grease does not suffer from such disadvantages, it can be applied easily and, in fact, produces a conductor which is not too difficult or messy to handle off the reels.

Insufficient time has really elapsed to confirm the resistance of this new grease to corrosive influences, but from a knowledge of its composition it can be predicted that the protective properties will be at least as good as those of greases (*a*) and (*b*).

If the principle of greasing a conductor is accepted, the most useful product to adopt is one which is both easy to apply and which gives the maximum degree of protection under practical conditions.

Mr. R. L. Davies (*at Chester*): A mean life of 25 years seems a little discouraging, even taking into account an additional 10 years with grease application. I have in mind particularly overseas areas which are just being developed and to which much steel-cored aluminium conductor is being exported. I note that most of the deterioration figures given in the paper refer to industrial conditions. Could the authors supply more information on the proportion examined from unpolluted atmospheres? Would they agree that, in the absence of industrial smoke and sea spray, 50–60 years would be a reasonable estimate of life? The authors should attempt to correlate the rate of deterioration with the degree of atmospheric pollution, as described for steel and zinc in Reference 5 of the paper.

One difference between the coastal and industrial types of attack is due to the higher conductivity of the wet corrosion product in coastal conditions. In the industrial case "bulge" attack must commence, but as soon as the aluminium and steel have been pushed apart a little by the corrosion product, the size of the galvanic cell is increased and its resistance becomes too high for the action to continue. Is any information available on the composition of the corrosion products which would substantiate this?

Reference 2 of the paper deals with the effect of minute amounts of copper. Have the authors any evidence to support their suggestion that these effects may apply in the case of atmospheric corrosion? I would expect corrosion to be worse at the centres of the spans, where the rain water drains, and we have noticed this type of effect on galvanized-steel guy-wires. Have the authors noticed it with steel-cored aluminium?

The outer aluminium wires must considerably reduce the available oxygen at the surface of the galvanized steel. Would it not therefore be better to use instead of zinc a coating metal such as tin with a high overvoltage, or would 80 : 20 tin-zinc alloy be better still? It has been shown by the Fulmer Research Institute to be superior to zinc or cadmium for steel bolts in aluminium.

Greasing must be very thorough, since an uneven coating may lead to differences of potential between different areas in the conductor, through differential aeration.

Mr. T. A. P. Colledge (*at Chester*): Has consideration been given to extruding round the central steel conductor a sheathing of aluminium? It seems that the dangerous corrosion takes place there. This sheathing might even be of sufficiently large cross-sectional area to take the full load and thus save the stranded formation of the cable and present a smooth surface to the elements.

Mr. E. A. Burton (*at Chester*): While most of the work has been done on 37/0·110 in s.c.a. conductor, there have been a few samples of conductors having different strand diameters. Have the authors experience of conductors having smaller strand diameters? I remember a sample of conductor from the Liverpool approach some years ago which had much smaller strands; the corrosion on these conductors was certainly severe and took the form of deep crater-like pits. There was no steel core. Would the authors comment on the effect of the size of strands on the problem of corrosion?

Mr. Spence referred to an unfortunate experience we had on measuring the resistance of the conductors on a complete line; so far as I know not much work was done in the early stages on the measurement of the resistance of the complete conductor. The cause of the trouble referred to by Mr. Spence was transference of fault current from the aluminium (which was badly corroded) to the steel, and the consequent burning of the latter. What are the authors' views on the measurement of the resistance of, say, a 20- or 30-mile line with a view to assessing its condition. It is not always easy to take a sample, although I agree that it is the better procedure.

At one time the full-load current of a 0·175 in^2 (37/·110 in) conductor was about 220 amp, and it is known that the steel can carry this current more or less continuously without affecting its tensile characteristics to any extent. The full-load current of such a line is now nearer 500 amp (excepting, of course, the emergency loading of 700 amp). Can the steel carry a current of 500 amp continuously without serious effects?

Mr. L. R. Cleworth (*at Chester*): Can the authors supply any information on the probable behaviour of the smooth-body s.c.a. conductor which seems to be gaining ground in Canada and the

United States? It is a much more compact conductor, and the surface area exposed to atmospheric conditions is much less than for a normal s.c.a. conductor.

Mr. L. J. Archer (*at Chester*): Mr. Spence suggested that all conductors should be greased. If the idea of the grease is to prevent electrolytic attack, is there any point in greasing non-composite conductors?

The figure of 12%, which is taken as a safe loss of strength and represents approximately 30% loss of aluminium, must, of course, depend on the composition of the conductor, and while it is doubtless a satisfactory guide for the 37/·110in conductor, it is not necessarily so for conductors of other stranding. For instance, the 12% loss of strength of the earth wire must represent 50% loss of aluminium. This can probably be tolerated in the earth wire, but it can scarcely be tolerated in a conductor.

On the question of resistance measurements mentioned by Messrs. Spence and Burton, the figures given would be far too optimistic. The weakening of the conductor might be very local, but nevertheless the conductor would fail at that point. Measurement of the resistance of a considerable length of conductor would not give a true indication.

I am puzzled why we have not had trouble with copper conductors held in galvanized-steel clamps. One would expect that the clamps would be attacked, the zinc being first removed from the clamps, and the copper then proceeding to attack the steel. Some years ago, trouble of this nature was experienced with a length of steel-cored copper conductor crossing the River Weaver, and it had to be replaced. The copper strands failed, but I believe the mechanism involved was that corrosion from the zinc and steel caused failure of the copper strands owing to bursting.

Mr. T. B. Airey (*at Chester*): It is generally agreed that almost pure aluminium conductors resist corrosion very much better than less pure conductors, and our present conductors contain approximately 99·5% aluminium. In Table 5 the silicon content varies between 0·15 and 0·23%, while the iron content varies between 0·17 and 0·37%. The manganese content scarcely varies at all—actually between 0·002 to 0·003%. Of course, it is necessary to have some kind of impurity in the aluminium so that it may be work-hardened in order to increase its tensile strength, and this impurity is usually silicon. Should not the silicon content be more closely controlled and the iron content eliminated so far as possible in order to obtain better results?

Mr. N. D. Clotworthy (*at Dublin*): I am not so much interested in overhead-line conductors as in the corrosion of aluminium alloys exposed to strongly marine atmospheres, but an examination of Figs. 6 and 7 of the paper for inner aluminium conductors might lead one to suppose that there are factors other than atmospheric ones which lead to deterioration. For instance, in a standard cable of stranded construction there must be small relative movement between strands, and thus friction and consequent wear. The introduction of grease surely reduces this effect and contributes to conductor life. Have the authors considered possible effects of this nature?

Mr. T. C. Timlin (*at Dublin*): For those engaged on rural electrification in Ireland it is rather unfortunate that the paper deals with conductors ranging in size from 220 to 115mm² and mostly having a double layer of aluminium strands. Since 1948, 40000 miles of s.c.a. conductor have been installed throughout the Irish rural networks on 10kV and low-voltage lines. The conductor sizes are almost entirely 50 or 25mm².

Another big fundamental difference is that there are many non-tension joints on our l.v. lines which have an average spur length of 250yd. These joints occur at connections on transformers, fuses and branch points, as well as at each end of the service to each house. We use some 200000 non-tension connections per year on these networks, and some 20% of them are bimetal types (aluminium–copper). It is clear that we are lik[ely] to experience far more trouble from corrosion or deteriorat[ion] of these joints than from corrosion of the conductor itself. [To] date, no manufacturer seems to have produced a bimetal c[on]nector which is both efficient and cheap.

In view of the voltage and current heating effects, can a 10[kV] lightly-loaded line or an l.v. line with medium current be expec[ted] to have a longer life than a high-voltage transmission line?

From the corrosion figures for the Hayle end of the Hay[le–] Fraddon line, would it be safe to assume that s.c.a. conduct[ors] erected more than, say, 2 miles from the open sea are not lik[ely] to be seriously affected by coastal corrosion?

Mr. A. Burke (*at Dublin*): We are not fully satisfied with [the] wisdom of using grease in rural areas. When it does deterior[ates] it may hasten rather than retard corrosion, either by becom[ing] stiff and cracking or by becoming absorbent and hold[ing] moisture. This may apply particularly to grease (*b*), wh[ich] contains bitumen. Initially it is more weather-resisting than [the] other greases, but when the constituents decompose there [is] danger of the bitumen residue accelerating corrosion, as it [does] when applied alone. At least partial drainage may follow [a] severe short-circuit, but in any case the heat will be deleteri[ous] either by breaking down the grease or to a less extent by caus[ing] stiffening. There will also be some stiffening with age.

Under the severe ice loads which occur in this country, ea[ch] layer of wires bears on the layer beneath with an extremely h[igh] pressure, so that no grease can remain at the crossing poin[ts]. Furthermore, the aluminium wires are permanently elongat[ed] so that on removal of load there will be a space between [the] steel and aluminium layers. Particularly if the grease stiffe[ns] it is too much to expect that these voids will not be open to [the] atmosphere at many places, thus leaving the bared crossing poi[nts] unprotected.

The greases developed are undoubtedly good and provide [an] economic solution to the problem of rapid corrosion in indust[rial] or coastal areas, but it still remains to be seen whether they [are] economic or even beneficial in areas where corrosion wo[uld] otherwise be light. What will be their effect in such areas af[ter], say, 30 years?

Mr. J. H. Dance (*at Newcastle upon Tyne*): The authors [do] not mention the effect of conductor tension on corrosion, [but] reference is made to the widely varying samples obtained fr[om] even the same span of conductor. One might advance the the[ory] that at certain points of the conductor the steel core and [the] aluminium strands have become welded together by the harden[ing] of the bitumen coating on the steel core, while at other positi[ons] the steel is free to move inside the aluminium under temperat[ure] changes. At these latter positions the corrosion rate may [be] greatest, since the aluminium has been subject to the great[est] stress and is therefore more prone to attack.

I regret that the authors have done no tests on conduct[ors] operating under reduced-tension conditions, such as th[ose] occurring in down leads into substations. These could ha[ve] discounted the theory that the tension of the conductor has a[n] important effect on the corrosion rate.

In Table 4, do the authors attach any significance to the f[act] that in only two instances has the tensile strength been the sa[me] as or reduced to a greater degree on the earth wire than the l[ine] conductor? I refer to the samples taken from lines in the Nor[th] Eastern Division. Is this a pointer to a geographical proble[m], because it seems, in general, to be a contradiction that these wi[res] are less prone to attack than line conductors.

In Section 5.2.3. reference is made to the bulging of conduct[ors] in coastal districts, and it is indicated that in certain cases t[he] effect occurs at regular intervals corresponding to the lay of [the] steel strands. I am unable to understand this reasoning, a

hought that the conductor would be uniform in cross-sectional rea at any given point along its length. In Section 5.3.2 details of accelerated corrosion tests are given to simulate coastal conlitions, and it is indicated that within 60 days on one test the zinc coating had been removed from the steel strands, and at this tage the process was reversed and aluminium was deposited on he steel. If this process is inevitable, would the authors use a zinc sheath between the aluminium and the steel in order to keep he original process of deposition of zinc going longer and thus engthening the life of the conductor, or would they dispense vith the galvanizing of the steel strands and use, say, stainless teel? This might even be an economical proposition if the life of the conductor were to be lengthened considerably.

Mr. L. A. Bates (*at Newcastle upon Tyne*): The classification of the test samples into industrial and coastal categories shows learly the different types of corrosion which can occur in these nvironments. I would have liked to have seen a further and listinct classification covering samples from rural areas only so hat a fairly accurate estimate of the life of s.c.a. conductors inder the best conditions would be known. This would be of particular interest in deciding whether to extend the use of s.c.a. conductors to h.v. distribution at lower voltages, i.e. 11 kV and 20 kV, for these lines can often be located entirely in rural conlitions. Nevertheless, the use of steel-cored aluminium for such ines must show a substantial overall long-term saving, paricularly when one considers the greater difficulty of conductor eplacement on lines of this category as compared with Grid lines.

In what way do the results given in the paper apply to service onditions? Is there a periodical review of feeder rating based on the probable corrosion rate, and if so, is it related to reduction of tensile strength or to conductivity? Has any work been done o show whether overheating due to very localized corrosion ccelerates the rate of corrosion or is a limiting factor for current ating.

The paper provides useful bases for assessing the probable life of plain aluminium conductors which, at present metal prices, offer an attractive alternative to copper. The probable life in ndustrial areas could vary considerably and their use should perhaps be avoided in heavily industrialized areas where, in any ase, there is little scope for l.v. overhead distribution.

Mr. A. B. Wood (*at Newcastle upon Tyne*): The authors have rrived at a mean life expectancy of 25–30 years based on a riterion of 12% loss in ultimate tensile strength when computed n accordance with B.S. 215. This is equivalent to stating that onductors which were originally erected with a safety factor of on the ultimate strength should be replaced when it has fallen o $1\frac{3}{4}$ owing to corrosion, principally of the aluminium. This is ot a particularly low figure when we consider that the proposed ew Overhead-Line Regulations advocate a safety factor of $1\frac{1}{3}$, which, although based on different loading conditions, represents considered safety limit. Furthermore, under service conditions he steel core carries rather more than its theoretical share of the oad, so that a given total percentage deterioration calculated n accordance with B.S. 215 is rather pessimistic, particularly if nost of the deterioration is confined to the aluminium strands, s is usual.

These points indicate that if the tensile strength is to be the nly criterion of conductor life, the figure of 12% total deterioraon is rather conservative, and a higher figure resulting in a onger service life seems to be indicated. The replacement gures mentioned by Mr. Schofield in the London discussion ould appear to bear this out. One might also argue that, if the onductor is initially strung with a larger factor of safety than used at present, a longer useful life could be expected. Could he authors indicate how they arrived at the figure of 12% total eterioration or its equivalent of 30% when expressed in terms of the aluminium alone? It would also be interesting to have some details of the life-expectancy criterion adopted by other countries. For example, the French have made some estimates of conductor life.

In Section 6.2 mention is made of a silicon-magnesium alloy conductor. When this type of conductor was introduced into this country, emphasis was laid on its ability to withstand atmospheric corrosion, and fairly large quantities were erected when the steel shortage 3–4 years ago made delivery of s.c.a. conductor rather haphazard. This alloy conductor seemed an ideal substitute for steel-cored aluminium, since although slightly more expensive, is still showed considerable economies over copper. It is surprising, however, to find that its life expectancy may be even less than that of steel-cored aluminium, and since the production of this alloy conductor appears to be increasing, it would be desirable to have fuller details of its behaviour.

Mr. R. A. Hore (*at Newcastle upon Tyne*): Why did the authors investigate laws of the type $d = kt^x$? It does not seem to be well known that the general dictum, "all things being more or less equal, one should choose the simpler law or hypothesis" can be substantiated on surer grounds than convenience. It can be proved that the simpler the law the greater is its prior probability, and this theorem is invaluable in saving time and misgivings. Laws of the type $d = kt^x$, where x is not an integer, have very small prior probabilities. The proof of the theorem involves difficult concepts, but its correctness may be demonstrated by successively fitting laws of increasing complexity (e.g. polynomials of increasing order), when it becomes apparent that the greater the number of degrees of freedom of the law the larger is the variance of its parameters. Thus there comes a stage after which there is no improvement in accuracy. A much simpler and more convincing method of justifying the use of a linear law would be to fit a quadratic law $d = at^2 + bt + c$ and to show that a is not significantly different from zero (e.g. by an analysis of variance).

Is there any significant difference between the two regression lines in Fig. 5? If not, a single line could be substituted, and it would be much easier to memorize as a "working rule."

In association with Mr. Wood, I would suggest the following method of determining the permissible deterioration before replacement, or more directly, the safe life of the conductor.

The regression line [for, say, industrial conditions (Fig. 5)] is determined from samples and represents the mean deterioration of all the conductors from which the samples were taken, i.e. there are as many conductors more severely corroded than is indicated by the regression line as there are ones less severely corroded; alternatively, any individual conductor has a 50% chance of being more severely corroded than is indicated by the regression line.

It is also possible to draw lines (above and below the regression line) such that the probability of more severe corrosion than is given by them is less than, say, x (in this particular case the analysis will be complicated by heteroscedacity, but it is none the less tractable). Let such a line be drawn with a value of x negligibly small. With an initial factor of safety of 2, the abscissa of the point at which this line has an ordinate of 50% is the safe life of the conductor for an x% probability of conductor failure. The corresponding ordinate of the regression line is the maximum permissible mean deterioration for an x% probability of conductor failure.

Of course, we still have to determine an acceptable value for x. But in so far as the solution obtained in this way has more meaning, I hope that the authors will concede that it is easier to decide on a reasonable and acceptable value. The fact that $x = 0$ is uneconomic (apart from being impossible) indicates that a value might be estimated on economic grounds.

Mr. J. V. Taylor (*at Newcastle upon Tyne*): In Section 6.1.4 the authors mention trouble experienced using "come-along" clamps, owing to the lack of friction between inner and outer layers of the conductor due to its being greased. The general adoption of the greased conductor, even if the grease is applied only to the steel core, would appear to preclude any further use of the snail clamp for anchoring fully-tensioned conductors, since the snail clamp utilizes friction to assist in the anchoring process, as distinct from the compression clamp where the steel core and the aluminium layers are anchored separately. If this is the case, the snail clamp appears to have no future except, perhaps, where there is no full line tension, such as in down leads. This is unfortunate, since snail clamps are cheaper than compression clamps and need no special field gear such as compressors. Furthermore, a compression clamp when once made is unadjustable and non-recoverable, and allows of no mistakes in marking off the exact conductor length, whereas the snail clamp can be recovered and repositioned if necessary. Nevertheless, the rejection of the snail clamp is a very minor matter compared with the probable extended life of many thousands of miles of conductor, particularly as the compression clamp has now been in entirely satisfactory use for some time.

Dr. J. S. Forrest and **Mr. J. M. Ward** (*in reply*): Messrs. Spence, Archer, Bates, Wood and Hore have referred to the maximum allowable figure for the deterioration of a conductor and the factors which determine it. In general, tensile strength is the best measure of conductor corrosion, and the figure of 12% total deterioration, although arbitrary, is a satisfactory guide in practice. The condition of the few conductors which have failed in service due to corrosion indicates that it would not be wise to raise this limit much. As Mr. Spence has pointed out, the effect of corrosion on the maximum current rating must be borne in mind. For various reasons, the percentage reduction in the current rating will be less than the percentage loss of mechanical strength of the aluminium strands, but in severe cases the current-carrying capacity might be reduced by 10–20%. The current rating should be reviewed if the resistance of the line has significantly increased.

The standard deviations given in Section 5.1.1 could be used to establish "confidence limits," as suggested by Mr. Hore, and the maximum permissible mean deterioration determined for a given probability of conductor failure, if the safe limit of conductor strength were known. Although the line may be designed initially with a safety factor of 2, the 50% deterioration quoted by Mr. Hore is unrealistic, since it would correspond to more than complete removal by corrosion of the aluminium strands.

Concerning the economics of greasing conductors, the incidental costs due to plant outage, mentioned by Mr. Spence, have not been included in our estimates. We welcome Dr. Priston's comments on the newly developed aluminium-base grease. The bitumen-oil-lime grease has properties very different from bitumen, and the possibilities envisaged by Mr. Burke do n seem to be at all likely. Grease does unfortunately limit the u of snail clamps, as mentioned by Mr. Taylor.

Messrs. Archer, Bates and Wood have discussed non-compos conductors. There is no possibility of electrolytic attack at t core in this type of conductor, which is an advantage in coas districts. Corrosion can occur on the outer surfaces and in t crevices between strands, however, and could be prevented greasing. Field tests are being made in collaboration with t manufacturers to compare the performance of aluminium a aluminium-alloy conductors under the same conditions.

In reply to Mr. Davies, a life of 50 years can be anticipat for s.c.a. conductors in unpolluted districts.

With regard to the possibility of other factors affecti deterioration, the condition of conductors in clean atmosph indicates that wear due to relative movement between aluminiu strands, as mentioned by Mr. Clotworthy, is negligible. Lo stresses of the type mentioned by Mr. Dance are unlikely accelerate corrosion of the aluminium. Where the tension low, however, as in down leads to substations, the ou aluminium strands are looser and the conductor is more read penetrated by corrosive elements. Examination of samples such conductor indicates that corrosion occurs more rapidly th on the conductors under line tension.

Replying to Mr. Burton, the smaller the diameter of t aluminium strands for the same cross-sectional area of co ductor, the greater is likely to be the effect of corrosion. N only will the ratio of the surface area to volume of each stra increase, but the number of inter-strand crevices in which c rosion can occur will also be increased. Careful measureme of the resistance of a complete line, corrected for temperatu can provide some indication of the overall condition of the co ductors. Local deterioration of a short length of the line m escape detection, however. A current of 500 amp in the st core of a $0{\cdot}175\,in^2$ s.c.a. conductor will cause failure due overheating in a very short time. It is essential to preve transfer of heavy load or short-circuit currents to the steel co

Regarding the effect of small amounts of copper, mention by Mr. Davies, the cause of rapid corrosion of an s.c.a. co ductor some years ago was traced to copper from the die us for drawing the aluminium strands.

In reply to Mr. Timlin, we think that the best method making bimetal connections is to use a bolted or compressi joint of simple design and adequate contact area protect against moisture by thorough greasing. The rate of corrosi decreases with increasing distance from the coast, but conducto strung several miles from the sea show signs of serious corrosi after 15 to 20 years. If the rates of corrosion of earth wire a line conductors at Hayle are compared, it can be seen that sing layer conductors are more prone to attack than double-la conductors if the cores are not adequately protected.

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THE CAPABILITY OF ALTERNATORS

By R. W. BRUCK, B.Sc., B.E., and H. K. MESSERLE, M.Eng.Sc., B.E.E.

(*The paper was first received 18th January, and in revised form 13th April, 1955.*)

SUMMARY

The method of constructing complete capability diagrams for alternators is presented. The various limits of operation, namely rotor and stator heating, stator-end heating and steady-state stability are considered both for a salient pole and for the special case of a round-rotor machine. Methods are given to enable the diagrams to be drawn for various terminal voltages and also for the case of a generator plus unit transformer.

LIST OF PRINCIPAL SYMBOLS

V_t = Rated terminal voltage of alternator.
V_t' = Terminal voltage other than rated value.

$$SCR = \text{Short-circuit ratio} = \frac{\text{Field current to give rated terminal voltage on open circuit}}{\text{Field current to circulate rated current on short-circuit}}$$

V_2 = Voltage of infinite busbar.
V = Synchronous-reactance voltage.
P = Real component of power.
Q = Reactive component of power at machine terminals.
Q_2 = Reactive component of power at load terminals.
X_d = Direct-axis synchronous reactance.
X_q = Quadrature-axis synchronous reactance.
X_e = Equivalent reactance of system excluding unit transformer.
X_t = Reactance of unit transformer.
δ = Angle between V_2 and V.
X_l = Leakage (or Potier) reactance.
V_l = Leakage-reactance voltage.
V_q = Quadrature-axis synchronous-reactance voltage.
V_c = Voltage correction for saturation.
V_h = Voltage on h.v. side of unit transformer.
γ = Angle between V_t and V.
I_d = Direct component of armature current.
I_q = Quadrature component of armature current.
$\cos\phi$ = Power factor.

(1) INTRODUCTION

In order to make full and economical use of an alternator it is essential that the operator clearly understands the factors influencing the maximum possible output of the alternator, and how the output may be changed. For the purposes of planning a system it is also essential to understand how the various alternator parameters are associated with the maximum output under various operating conditions, so that the selection of the most suitable machine from both economic and engineering points of view is ensured. It is for these reasons that a graphical representation of the alternator output, in megawatts and reactive megavolt-amperes, has been developed. This diagram, which is called a capability diagram, shows the limits to which an alternator may safely be loaded for any operating condition from zero power-factor lag to zero power-factor lead. Rectangular Cartesian co-ordinates are used with the MW axis vertical, positive values in MVAr being to the right of the origin. The convention for reactive power is that positive MVAr are absorbed by an inductive load, i.e. for lagging current.

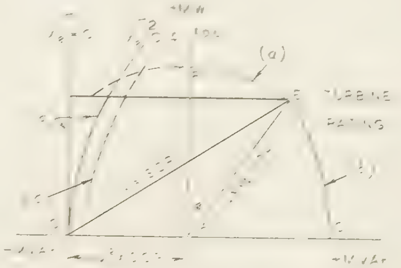

Fig. 1.—Construction of capability curve for nominal terminal voltage $V_t = 1$ p.u.

$\cos\phi$ = Rated power factor.
(*a*) Stator-heating limit.
(*b*) Rotor-heating limit.
(*c*) Stator end-heating limit.
(*d*) Stability limit.

An example of a capability diagram is given in Fig. 1. There are four distinct sections to the complete curve:

(*a*) The armature heating limit.
(*b*) The rotor heating limit.
(*c*) The heating limit of the end structure of the stator.
(*d*) The steady-state (or dynamic) stability limit.

There is also the limit of operation of the turbine, but that will not be considered in the paper. The maximum turbine rating in megawatts is taken as equal to the rating in megawatts of the alternator at rated power factor.

The concept of the capability diagram was initially suggested by Szwander[1] for round-rotor machines, neglecting saturation. Methods have been developed since for constructing the capability diagram for voltages differing from rated value for a round-rotor machine taking saturation into account[5] and also for an unsaturated salient-pole machine.[6]

In recent years attention has been given to the steady-state stability limit with and without continuous regulation, with particular reference to increasing this limit.

The paper attempts to give the method of constructing the complete capability diagram for all conditions of operation, and is intended primarily for the practising power engineer to enable him to construct capability diagrams expeditiously. The derivation of most parts of the diagram is well established but some additional generalizations are considered in the paper. The method of determining the curve of the steady-state stability limit for a salient-pole alternator has hitherto been available only for the alternator working directly on to an infinite busbar,[6] and it is extended here to include the effects of a series impedance. The derivation of the limits at various terminal voltages, as well as the added construction to take account of saturation, has been simplified.

Throughout the paper per-unit (p.u.) quantities will be used, the base being rated alternator quantities.

[illegible]

The effect of continuous regulation is covered in another paper,[7] in which a general approach to machine stability and generalized machine equations are applied.

(2) CAPABILITY OF RATED TERMINAL VOLTAGE

The method of construction of the capability curve for rated terminal voltage is first discussed, before consideration is given to capabilities at other terminal voltages. This is done mainly because generators usually operate at, or very close to, the rated voltage.

The capability curve may be easily and quickly constructed for rated terminal voltage. It will often be found that only the diagram for rated terminal voltage is required, as for generators in large power stations supplying local loads, or if on-load tap-changing transformers are provided.

(2.1) Stator-Heating Limit

The stator-heating limit, being due to the armature resistance, is a current limit, and the maximum allowable stator current is taken to be that current which corresponds to the maximum continuous rating in megavolt-amperes. The stator-heating limit is represented on the complex power plane by a circle having its centre at the origin. This is clearly so, since a constant current output at a constant terminal voltage represents a constant number of megavolt-amperes and these constants at different power factors describe a circle about the origin as centre.

(2.2) Rotor-Heating Limits

(2.2.1) Round Rotor.

The maximum rotor current is taken to be that current which flows in the rotor windings when the generator is operating at rated load, rated voltage and rated power factor.

By neglecting saturation effects, a very simple method of obtaining the rotor-heating limit for 1 p.u. (nominal) terminal voltage is available. It can be shown[2] that this limit is represented by a circle having its centre on the MVAr axis at $(-1/X_d)$ from the origin, and radius to the point corresponding to the rated power at rated power factor. In order to take some account of saturation the short-circuit ratio is usually taken instead of $1/X_d$, and, as shown in Fig. 1, the centre is at O and the radius is OE. The arc EC follows as the rotor-heating limit. The method may also be evolved as a special case of the salient-pole rotor discussed in Section 2.2.2.

If saturation had been considered the centre of the circle would have been shifted somewhat, but the radius would still have been drawn to E and the effect would be to change the position of point C slightly in Fig. 1.

(2.2.2) Salient-Pole Rotor.

The construction for the rotor-heating limit of a salient-pole alternator is more complicated than that for a round-rotor machine. It is based on a method described by Walker.[6]

The construction follows from a 2-reaction vector diagram as shown in Figs. 2 and 3. In Fig. 2 the conventional 2-reaction vector diagram is AGBDA, familiarity with which is assumed. This can be reduced to a form similar to a round-rotor vector diagram by replacing V by V_1, where V_1 corresponds to the excitation vector based on round-rotor theory, and $BC = I_q(X_d - X_q)$ is added at D, as shown, DH being equal to BC. The excitation-voltage vector is HC = DB, and this is produced to cut AD produced at F. A semicircle is then constructed on FD which is equal to $V_t(X_d - X_q)/X_q$. The excitation vector is represented by the intercept on a ray from F between the semi-

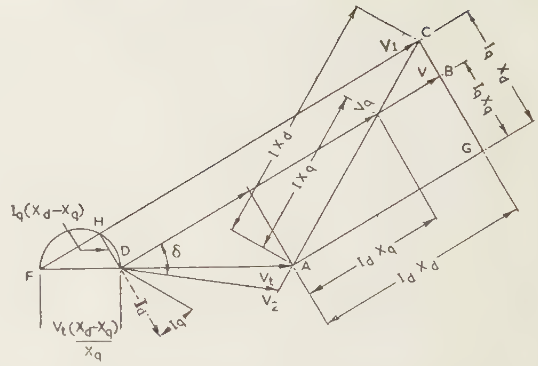

Fig. 2.—Vector diagram for salient-pole machine showing additional construction to make diagram similar to a vector diagram for round-rotor machine.

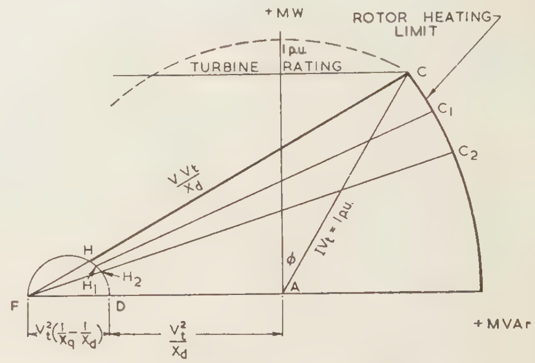

Fig. 3.—Rotor-heating limit for salient-pole machine derived from construction of Fig. 2.

circle on FD and C, the rated power factor on the 1 per-unit current circle.

By multiplying all factors throughout by V_t/X_d the voltage vector diagram is converted to a volt-ampere (or MVA) diagram still on a per-unit basis. This is shown in Fig. 3.

AC = 1 p.u. is the radius of the armature-heating limit, as was for a round-rotor machine. The diagram is drawn for rated power factor; hence HC corresponds to the limiting value of rotor current. At other power factors the rotor-heating limit is obtained by marking off $H_1C_1 = H_2C_2$, etc. = HC on rays from F and joining CC_1, C_1C_2. The curve thus obtained is very close to a circle with radius DC and centre at D. Thus as far as the capability curve at rated voltage is concerned, the round-rotor method for constructing the rotor-heating limit is usually accurate enough for salient-pole machines.

(2.3) Stator End-Construction Heating Limit

In round-rotor alternators when operation tends towards the leading-power-factor region, heating of the end-construction of the stator may arise, possibly with very serious results.[4] The heating is caused by the rotating armature and leakage flux cutting the various metal parts in the end structure.

Part of the total armature leakage flux is end-leakage caused by the overhanging end connections. The path of this flux, which is always along the line of lowest reluctance, varies with the degree of saturation of the rotor iron and with the power angle δ. At leading-power-factor operation, when the excitation is low and the rotor iron is not highly saturated, the end leakage-flux path is from the end of the stator core through the end-connection loops and then radially into the field-retaining

ing. The path continues circumferentially around the retaining ing for one pole-pitch, and back into the stator by a similar oute. This flux pattern rotates at synchronous speed, and in loing so cuts the various iron parts of the stator end-construction, ausing them to heat up if the flux density is high. The end aminations of the stator core, which have eddy currents induced n the plane of lamination, may also suffer from this heating effect.

The heating may become serious in the under-excited region vhen the field is only slightly saturated, whereas when the field s fully saturated the flux configuration is changed and the roblem of end heating does not arise. There is no such end eating in salient-pole machines because of the high reluctance of the leakage-flux path.

Modern alternators are far less prone to stator-end heating han alternators built about 20–30 years ago, but care should be xercised and a heat test should be made on any machine which nay have to be operated under conditions where this trouble ould arise. For arranging a test the position of the thermo-ouples should be carefully studied so as to obtain the positions of highest temperature rise. The manufacturers' advice should e sought.

An indication of the region on the capability diagram in which tator heating might occur is shown in Fig. 1.

2.4) Stability Limit with Non-Continuously Acting Regulation

The criterion for stability will be derived for a salient-pole nachine with non-continuous regulation by the usual method tarting from the steady-state vector diagram.

A non-continuously acting regulator has a definite range of nsensitivity, or dead band. The voltage must deviate sufficiently rom the nominal or reference value to move out of the dead and, and this makes the regulator non-continuous in action. n example is the quiescent regulator. A continuously acting egulator has no region of insensitivity or dead band and begins o respond immediately, as in the amplidyne regulator.

The procedure is to derive an expression for the power output of the alternator and to find the condition of maximum output y differentiation. The result as obtained for a salient-pole nachine is complex, but the condition for a round-rotor machine uickly follows as a special case.

The power output of the alternator at the load is given by

$$P - V_2\bar{I} \cdot P \cdot jQ_L \quad . \quad . \quad . \quad . \quad . \quad (1)$$

As shown in Section 8, P and Q_L can be expressed as follows:

$$P = \frac{V_2 V \sin\delta}{(X_e + X_d)} + \frac{V_2^2 \sin\delta\cos\delta(X_d - X_q)}{(X_e + X_d)(X_e + X_q)} \quad . \quad . \quad (2)$$

$$Q_L = \frac{V_2 V \cos\delta}{(X_e + X_d)} - \frac{V_2^2}{2}\left(\frac{1}{X_e + X_q} - \frac{1}{X_e + X_d}\right)$$

$$- \frac{V_2^2}{2}\cos 2\delta\left(\frac{1}{X_e + X_q} - \frac{1}{X_e + X_d}\right) \quad . \quad (2a)$$

The machine becomes unstable when P is a maximum, i.e.

$$\frac{\partial P}{\partial\delta} = 0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

or

$$V_2 V\cos\delta + V_2^2\cos^2\delta\left(\frac{X_d - X_q}{X_e + X_q}\right) - V_2^2\sin^2\delta\left(\frac{X_d - X_q}{X_e + X_q}\right) = 0 \quad . \quad . \quad . \quad . \quad (4)$$

This is the condition of stability for a non-continuously regulated salient-pole alternator. For convenience in representation and plotting, eqn. (4) may be expressed in terms of real and reactive power (P and Q) thus

$$P^4 + P^2\left\{A\left[A - \left(\frac{1}{X_e} - Q\right)\right] + \frac{B}{X_q X_e}\right\} - A^3\left(\frac{1}{X_e} - Q\right) = 0 \quad . \quad . \quad . \quad . \quad (5)$$

where $A = \left(\frac{1}{X_q} + Q\right)$

Q being the reactive power at the alternator terminals and

$$B = \frac{(X_q + X_e)^2(X_d - X_q)}{X_q^2(X_d + X_e)}$$

This equation is plotted in Fig. 4 for an alternator having synchronous reactances $X_d = 1\cdot32$ p.u. and $X_q = 0\cdot69$ p.u., and system reactances $X_e = 0\cdot4$ p.u. and $0\cdot0$ p.u.

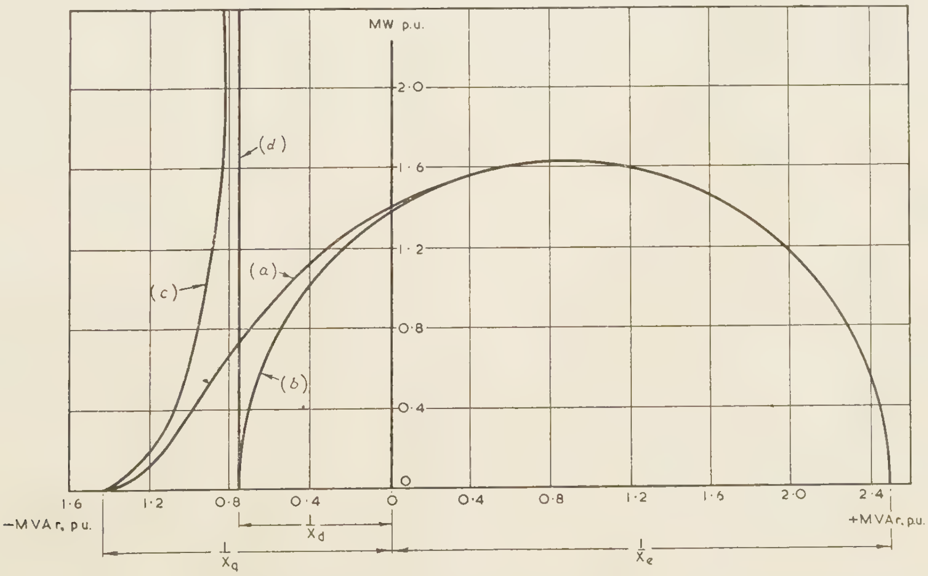

Fig. 4.—Steady-state stability limits.

(a) Salient-pole machine; $X_d = 1\cdot32$ p.u.; $X_q = 0\cdot69$ p.u.; $X_e = 0\cdot4$ p.u.
(b) Round-rotor machine; $X_d = 1\cdot32$ p.u.
(c) Salient-pole machine: $X_d = 1\cdot32$ p.u.; $X_q = 0\cdot69$ p.u.; $X_e = 0$ p.u.
(d) Round-rotor machine; $X_d = 1\cdot32$ p.u.; $X_e = 0$ p.u.

When the substitution $X_q = X_d$ is made in eqn. (5) the condition for a round-rotor machine follows as

$$P^2 = \left(\frac{1}{X_d} + Q\right)\left(\frac{1}{X_e} - Q\right) \quad . \quad . \quad . \quad . \quad (6)$$

being identical with

$$P^2 + \left[Q - \frac{1}{2}\left(\frac{1}{X_e} - \frac{1}{X_d}\right)\right]^2 = \left[\frac{1}{2}\left(\frac{1}{X_d} + \frac{1}{X_e}\right)\right]^2 \quad . \quad (7)$$

which represents a family of circles with centre at

$$+j\frac{1}{2}\left(\frac{1}{X_e} - \frac{1}{X_d}\right) \text{ from the origin}$$

and radius $$\frac{1}{2}\left(\frac{1}{X_d} + \frac{1}{X_e}\right)$$

In Fig. 4 is also shown a curve for the stability limit of a round-rotor machine having the same value of X_d as the salient-pole machine for which the stability curves are drawn.

If in eqn. (5) the substitution $X_e = 0$ is made, the equation reduces to

$$P^2 = \frac{-\left(\frac{1}{X_q} + Q\right)^3}{\left(\frac{1}{X_d} + Q\right)} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

which is identical with the equation derived in Reference 6.

In the over-excited region saliency has little effect on the stability limit, whereas in the under-excited region the stability limit is considerably greater for a salient-pole than for a round-rotor machine. This is as would be expected, since, for a large field current causing synchronizing power, the effect of the small power due to saliency (the second term in the right-hand side of eqn. 2) is not noticeable.

In plotting the curve for a salient-pole machine it is only necessary to consider accurately the under-excited region; the remainder of the curve can be completed with a circle as for a round-rotor machine.

In practice, it is impossible to operate on the stability limit, and a margin must be kept between the practical and theoretical operating limits. The usual method is to take a margin of 10% of the output in megawatts with a constant excitation. The method of deriving the practical limit is shown in Fig. 5, the procedure

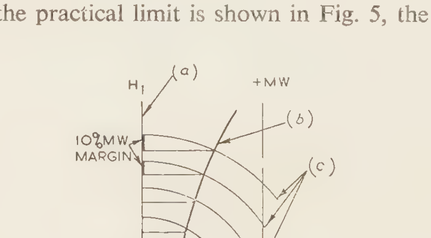

Fig. 5.—Construction of practical stability-limit curve.

(a) Theoretical stability limit (X_e = 0 p.u.).
(b) Practical stability limit (X_e = 0 p.u.).
(c) Circles of constant excitation V.

being to take a circle of constant excitation and reduce the output in megawatts along that contour by 10% from the point on the theoretical limit. It is worth mentioning that the shape of the practical stability-limit curves is only slightly affected by changes in X_d, and a template of these curves can be prepared if a number of capability diagrams are to be drawn.

(3) CAPABILITY AT TERMINAL VOLTAGES OTHER THAN RATED VALUE

Alternators which are located in or very close to a city and supply a local load from the alternator busbars are usually required to maintain a constant voltage to close limits. When the alternator does not supply a local load, as in the case of a power station situated at a distant coal-field or a hydro-electric station, transmission voltage-control is necessary, and although common practice has been to use on-load tap-changing transformers, voltage control is sometimes obtained at the alternator terminals and fixed-ratio transformers are used. For these cases, as for planning, it is necessary to have a good understanding of how the alternator behaves at terminal voltages other than the rated voltage, and a set of capability diagrams for various terminal voltages is very useful.

For the construction of capability diagrams (rotor-heating section) at various terminal voltages, it is necessary to consider saturation, otherwise a misleading result may be obtained. The saturation curve is required and the short-circuit characteristic for the alternator, as well as the value of the leakage (or Potier) reactance, must be available.

(3.1) Armature-Heating Limit

Since the armature-heating limit is dependent only on the armature current, if expressed in megavolt-amperes this limit is proportional to terminal voltage. Thus at, say, V_t = 1·05 volt p.u. the armature-heating limit in megavolt-amperes is a circle with centre at the origin and radius equal to 1·05 p.u. The lettering used in Fig. 7 corresponds to that used in Fig. 1.

(3.2) Rotor-Heating Limit

In Section 2.2 the rotor-heating section of the capability diagram has been discussed on the basis of an unsaturated vector diagram where the rotor-heating limit clearly corresponds to the maximum rotor current. It must be remembered, however, that all quantities expressed in per-unit terms (including rotor current) are referred to the armature, and that a linear relation has been assumed between rotor current and the corresponding values at the armature, namely active power (MW) and reactive power (MVAr).

When saturation is considered, the radius of the rotor-heating limit (on the "MW/MVAr" diagram) will be greater than if saturation is neglected, since for the saturated condition a greater rotor current corresponds to a given value of excitation voltage.

As was pointed out in Section 2.2.1, for a 1 p.u.-voltage diagram the effect of a small change of radius is very slight; however, when a curve for a different terminal voltage is constructed the radius and centre must be accurately known, since any approximation in either affects the result directly. The object is, then, to obtain accurately the radius (and centre) of the rotor-heating limit at rated voltage when saturation is considered. The radius for another voltage may then be found by direct proportion as described later in this Section.

In Fig. 6 are shown the open and short-circuit characteristics of an alternator (OY and OM respectively). Using a modified form of saturation-corrected vector diagram, the radius of the rotor-heating limit is found first for rated terminal voltage, and then, the same method being used together with the determined value of rotor-heating limit, another diagram is constructed for the new terminal voltages.

Referring to Fig. 6, OA = V_t, the alternator terminal voltage, and OAE is the unsaturated voltage vector diagram at full load

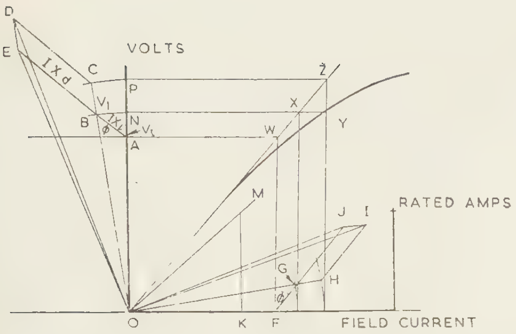

Fig. 6.—Saturation characteristics, and method of determining saturation correction.

and rated power factor. OFJ is the unsaturated field-current vector diagram corresponding to OAE, which is drawn in the most suitable quadrant and not in correct phase relation.

The field current corresponding to open-circuit terminal voltage on the unsaturated basis is OF, and FJ (=OK) is the rated current short-circuit excitation at rated power factor, OG is the air-gap excitation, and FG, which corresponds to the voltage drop across the leakage reactance X_l, is found by proportion, namely FG/FJ $= X_l/X_d$ or otherwise. The point B and V_l, the leakage-reactance voltage, are found from similar triangles or again by proportion.

The voltage and field-current vector diagrams for terminal voltage V_t have thus been found, and the necessary saturation correction is now made.

It was assumed that NX = OG was the field current corresponding to V_l, but the true value is NY = OH and the increase due to saturation is XY = GH = JI. Thus OI is the actual field current for V_t at rated power factor, and the field-current vector diagram for actual saturated conditions is derived. The unsaturated voltage vector diagram which corresponds to the field-current diagram is derived similarly, the saturation correction V_c being YZ = NP = ED.

The basic vector diagram for the construction of the rotor-heating limit is a volt-ampere diagram and is derived from the voltage vector diagram OAD by multiplying throughout by V_t/X_d. For convenience in construction of the rotor-heating limit the saturation correction is added at O instead of at B or E, and the vector diagram is turned into the position for which the capability curve is drawn, as shown in Fig. 7, where OF $= (V_cV_t)/X_d$ per unit.

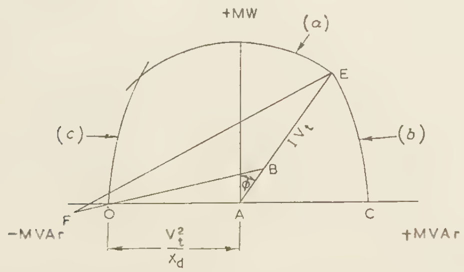

Fig. 7.—Capability diagram for conditions at machine terminals taking account of saturation.

(a) Stator-heating limit.
(b) Rotor-heating limit.
(c) Theoretical stability limit; $X_e = 0{\cdot}4$ p.u.

With centre F and radius FE the rotor-heating limit is described. A small approximation is made, since OF varies with power factor, but the effect on the rotor-heating limit is small.

If the centre of the rotor-heating limit determined by the above method is compared with the result of the method described in Section 2.2.1 it will be noticed that the position of the centre when saturation is taken into account is further away from the origin, thus giving a longer radius. The radius FE determined in this way gives the rotor-heating limit in terms of $V(V_t/X_d)$ per unit, where V represents the adjusted rotor current for limiting conditions and is fixed, being independent of V_t, and where, in this case, $V_t = 1$ volt p.u.

At any other value of V_t (say, V_t') the radius of the rotor-heating circle will be $V(V_t'/X_d)$ per unit, and is easily obtained by proportion. The centre is found by a method similar to that described for rated voltage; the saturation correction, however, will be different and OA becomes $V_t'^2/X_d$.

To include saturation in the case of a salient-pole machine, equivalent values of X_d could be considered, as described by Crary.[8]

(3.4) Stability Limits

In Section 2.4, eqn. (5) for the general case of steady-state stability for an alternator with non-continuous regulation was derived for $V_t = 1{\cdot}0$, for simplicity. For other values of V_t it is necessary to substitute P/V_t^2 for P, and Q/V_t^2 for Q.

For the special case of the round-rotor machine this gives a set of circles having centre at

$$+j\frac{V_t^2}{2}\left(\frac{1}{X_e}-\frac{1}{X_d}\right)$$

from the origin and radius

$$\frac{V_t^2}{2}\left(\frac{1}{X_e}+\frac{1}{X_d}\right)$$

The value of the direct-axis synchronous reactance to be taken for stability calculations is the unsaturated one, since the field is under-excited in any practical operating condition where steady-state stability needs to be considered.

(4) CAPABILITY OF ALTERNATOR AT THE H.V. SIDE OF A UNIT TRANSFORMER

An arrangement usually employed is to have each alternator connected to the station tie busbars through its own transformer, with no connection between the alternator terminals. The transformers are then called unit transformers. The power fed to the tie busbar is then of importance since it is the available power from the station, usually referred to as sent-out power. Clearly the reactance of the transformer (resistance may be neglected) causes reactive power losses and the available reactive power at the tie busbars is then reduced. The available output is further reduced in active and reactive power by that consumed by station auxiliaries, but these may be considered as a load, or alternatively the rating of the alternator may be reduced accordingly. Only the effect of reactive losses in the unit transformers will be considered here, and the construction is made for a fixed voltage on the h.v. side of the unit transformer.

The value of X_e which refers to the system reactance only is the same as used in Sections 2 and 3. The transformer reactance X_t is additional to X_e. If, on the other hand, X_t were included in X_e the diagram would refer to a different value of system reactance. In that case the effect would be to shift the MW axis to the right by X_t per unit.

(4.1) Stator-Heating Limit

Since at all points on the stator-heating limit the current is 1 p.u. the I^2X reactive power loss is jX_t, where X_t is the transformer reactance. This causes the centre of the stator-heating

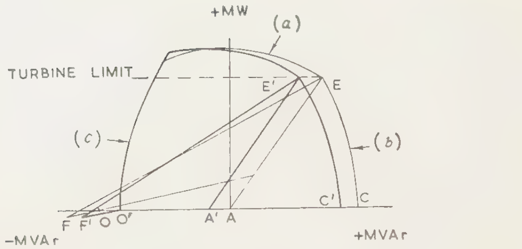

Fig. 8.—Capability diagram (primed letters) for h.v. side of unit transformers.

(a) Stator-heating limit.
(b) Rotor-heating limit.
(c) Theoretical stability limit.

limit to be shifted to $(-jX_t)$ from the origin in the complex power plane (point A′ in Fig. 8).

(4.2) Rotor-Heating Limit

A construction similar to that described in Sections 2.2 and 3.2 applies to the rotor-heating limit, except that V_t is replaced by V_h (the voltage on the h.v. side of the unit transformer), which has the value

$$V_h^2 = (V_t - IX_t \sin \phi)^2 + (IX_t \cos \phi)^2$$

In Section 2.2 it was shown that the centre of the rotor-heating-limit circle was at F in Fig. 7, where $OA = V_t^2/X_d$, and that OF was the saturation correction.

When V_t is replaced by V_h, and X_d by $(X_d + X_t)$ to include the effect of the transformer, the centre of the circle is moved to F′ (Fig. 8), where

$$O'F' = OF\frac{V_h}{V_t}\frac{X_d}{X_d + X_t}$$

and

$$O'A = \frac{V_h^2}{X_d + X_t}$$

The radius of the rotor-heating circle is now F′E′ instead of FE (as in Section 2.2) such that $EE' = I^2X = jX_t$.

(4.3) Stability Limit

Here again V_t is replaced by V_h and X_d by $(X_d + X_t)$ giving, for a round-rotor machine, the centre of the stability circle at

$$+j\frac{V_h^2}{2}\left(\frac{1}{X_e} - \frac{1}{X_d + X_t}\right)$$

from the origin and radius

$$\frac{V_h^2}{2}\left(\frac{1}{X_e} + \frac{1}{X_d + X_t}\right)$$

(5) CONCLUSIONS

The construction of capability curves for round-rotor and salient-pole machines has been presented for rated and other terminal voltages, and a method for correcting for saturation has been included. A set of diagrams drawn for a particular alternator will appear as in Fig. 9 in which the light curves refer to the alternator terminals and the heavy curves to the h.v. terminals.

A few points of interest are worth mentioning. In practice the lowering of the terminal voltage of an alternator, which is not an unusual occurrence, may cause either good or bad results, not always fully understood by operators. Fig. 9 helps to clarify these effects. For the optimistic case of $X_e = 0$ p.u. the diagram for $V_t = 1{\cdot}0$ p.u. shows that the alternators can absorb 7 MVAr at 30 MW generated (measured

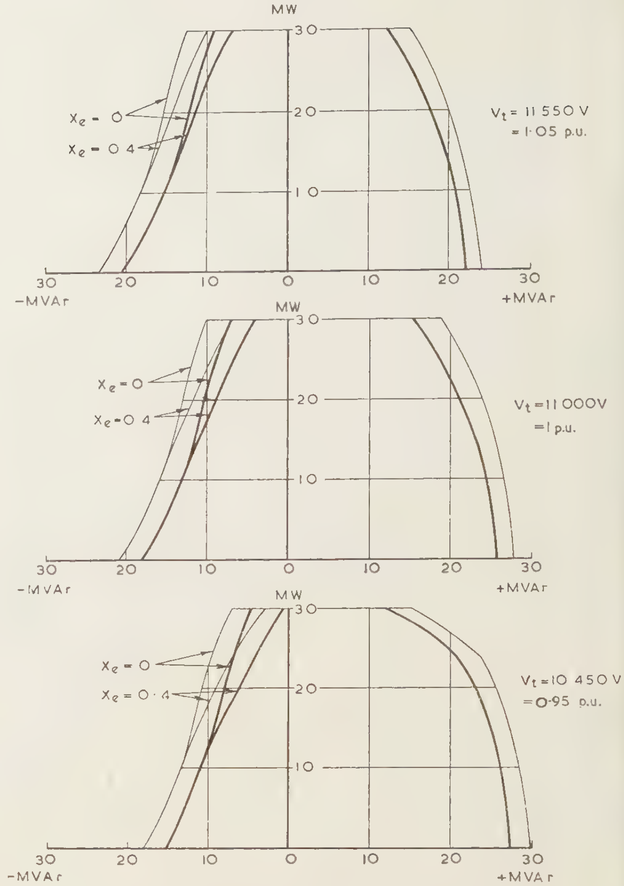

Fig. 9.—Capability curves of alternator.

——— At alternator terminals, } for the following conditions:
▬▬▬ At 132 kV side of unit transformer,

35·29 MVA.
30 MW.
cos ϕ = 0·85.
S.C.R. = 0·72. } at 11 000 volts.
X_d (unsat.) = 1·47 p.u.
X_l = 0·156 p.u.
X_t = 0·09 p.u.

at the 132 kV terminals). If the terminal voltage is reduced to 0·95 p.u. this figure is reduced to 5 MVAr. In practice, X_e is never zero and a value 0·4 p.u., although a little higher than usual, serves to demonstrate the point that the reduction of V_t from 1·0 to 0·95 p.u. now causes the reactive power which may be absorbed to be reduced from 5 MVAr to almost zero. With regard to steady-state stability, the danger of reducing the alternator terminal voltage on a system of high system-reactance is thus apparent. Where large power swings are also possible, such as at power stations near rolling-mills, the condition is further aggravated. However, it is a well-established fact that the use of continuously acting voltage regulators can move the stability limit to a region where it is no longer the prime consideration.[7]

At lagging power factors a reduction in terminal voltage enables more reactive power to be generated. Referring to Fig. 9, at 20 MW and with $V_t = 1{\cdot}0$ p.u. it may be seen that 21 MVAr can be sent out, but if the terminal voltage is now reduced to 0·95 p.u. the value rises to about 23 MVAr. This rise occurs only in the region where the stator heating is not limiting, and is of use only if tap-changing transformers or series regulators are available to enable the extra reactive power to be sent out. If the terminal voltage is reduced too far, the available reactive power is again reduced owing to the stator-heating limit.

As pointed out in Reference 6, it would be most convenient for the operating staff to have such a set of diagrams for each alternator to be used with a combined watt- and VAr-meter which reads active power vertically and reactive power horizontally on a single meter face. Such meters are sometimes referred to as vector meters. When the operating voltage changes, the diagrams can be replaced either manually or automatically. A suggested method is to have a slide projector, projecting the diagram on to the meter, and to use an automatic voltage-sensitive relay to move the appropriate slide into position for the particular voltage. Circles of constant excitation would also be included on operating diagrams and the operator would thus be given a complete representation of the loading condition of the alternator on a single meter.

(6) ACKNOWLEDGMENTS

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(8) APPENDIX

(8.1) Derivation of the steady-state stability limit of salient-pole and round-rotor alternators with non-continuously acting regulation.

The power output of the alternator, as shown in Section 2.4, is given by

$$\begin{aligned} P &= V_2\bar{I} \\ &= (V_2\cos\delta\, I_q + V_2\sin\delta\, I_d) + j(V_2\cos\delta\, I_d + V_2\sin\delta\, I_q) \\ &= P + jQ_L \end{aligned}$$

It may easily be shown that

$$P = \frac{V_2V\sin\delta}{X_e + X_d} + \frac{V_2^2\sin\delta\cos\delta(X_d - X_q)}{(X_e + X_q)(X_e + X_d)}$$

The power output is maximum and stability is limiting when

$$\frac{\partial P}{\partial\delta} = 0$$

or $$V_2V\cos\delta + V_2^2(\cos^2\delta - \sin^2\delta)\frac{(X_d - X_q)}{(X_e + X_q)} = 0$$

which is the usual form of the stability criterion.

In order to change eqn. (4) into a form which may be plotted on the capability diagram, V_2, V and δ must be changed to the new variables P and Q, representing MW and MVAr, respectively.

It will be assumed that $V_t = 1\cdot0$ p.u.

The substitutions required are

$$P = I\cos\phi \qquad (9)$$

$$Q = -I\sin\phi \qquad (10)$$

$$I_q = I\cos(\gamma - \phi) \qquad (11)$$

$$I_d = I\sin(\gamma - \phi) \qquad (12)$$

$$I_qX_q = \sin\gamma \qquad (13)$$

$$V_q - I_dX_d = \cos\gamma \qquad (14)$$

$$V_q = V\frac{(X_e + X_q)}{(X_e + X_d)} + V_2\cos\delta\frac{(X_d - X_q)}{(X_e + X_d)} \qquad (15)$$

$$V_2\sin\delta = \sin\gamma\frac{(X_q + X_e)}{X_q} \qquad (16)$$

$$V_2\cos\delta = \cos\gamma - I_dX_e \qquad (17)$$

From eqns. (9), (10), (11), (12) and (13) we have

$$\cot\gamma = \frac{1}{PX_q} + \frac{Q}{P} \qquad (18)$$

Hence also $\sin\gamma$ and $\cos\gamma$ may be written in the same terms. From eqn. (16) we have

$$V_q = \cos\gamma(1 + X_qQ) + X_qP\sin\gamma \qquad (19)$$

Substituting eqns. (15), (16), (17), (18) and (19) in eqn. (4) and simplifying gives

$$P^4 + P^2\left\{A\left[A - \left(\frac{1}{X_e} - Q\right)\right] + \frac{B}{X_eX_q}\right\} - A^3\left(\frac{1}{X_e} - Q\right) = 0$$

where $$A = \left(\frac{1}{X_q} + Q\right)$$

and $$B = \frac{(X_q + X_e)^2(X_d - X_q)}{X_q^2(X_d + X_e)}$$

This is the equation of the steady-state stability limit of a salient-pole machine.

For a round-rotor machine $X_d = X_q$ and $R = 0$, and eqn. (5) reduces to

$$\left[P^2 - \left(\frac{1}{X_e} - Q\right)\left(\frac{1}{X_d} + Q\right)\right]\left[P^2 + \left(\frac{1}{X_d} + Q\right)^2\right] = 0 \qquad (20)$$

Since P^2 must be positive,

$$P^2 = \left(\frac{1}{X_d} + Q\right)\left(\frac{1}{X_e} - Q\right)$$

Eqn. (6) is identical to

$$P^2 + \left[Q + \frac{1}{2}\left(\frac{1}{X_e} - \frac{1}{X_d}\right)\right]^2 = \left[\frac{1}{2}\left(\frac{1}{X_d} + \frac{1}{X_e}\right)\right]^2$$

which represents a family of circles having centre at

$$+ j\frac{1}{2}\left(\frac{1}{X_e} - \frac{1}{X_d}\right)$$

from the origin and radius equal to

$$\frac{1}{2}\left(\frac{1}{X_d} + \frac{1}{X_e}\right)$$

It is easily shown that all stability curves cut the Q-axis at

$$Q = -\frac{1}{X_q}\left(\text{or } -\frac{1}{X_d} \text{ for a round-rotor machine}\right)$$

and at $$Q = +\frac{1}{X_e}$$

Eqn. (7), which can be obtained more simply by puttin[g] $X_d = X_q$ initially and proceeding from the power-output equatio[n] as described in textbooks, has been included only for the sak[e] of completeness, and as a test of eqn. (5).

DISCUSSION ON "THE TECHNIQUE AND DEVELOPMENT OF AUTOMATIC WINDING IN MINE SHAFTS"*

NORTH MIDLAND UTILIZATION GROUP, AT LEEDS, 17TH NOVEMBER, 1953

Mr. P. H. Harvey: For raising and lowering men and materials it is difficult to see how any improvement can be made to using conveyances attached to ropes. The authors' proposals follow lift practice in many ways, and the use of several ropes and friction drives has been the practice in lifts for many years. However, for raising minerals it is possible that the skip or cage winder, which uses a big area of the mine shaft, may eventually be supplanted by the hydraulic pump, the mineral being pumped up in suspension. A pilot plant in America of this type has an output of 240 tons per hour through a 10 in pipe in a shaft 365 ft deep.

So far as the accident figures given are concerned, it would be interesting to have comparable figures on automatic lifts and winders on a basis of passenger trips for this country and America. These figures would help to justify, on the score of safety, automatic winding or control from the conveyance.

The definitions given for balanced, unbalanced and compensated winding are not in general use. Balanced winding usually implies that two conveyances are used producing opposing torques on the drive shaft, and with unbalanced winding there is no opposing torque to the one conveyance from another.

Better results are obtained in practice than those shown in Fig. 17; this is because there are both electrical and mechanical braking effects. However, if the power is removed and the "suicide" made operative (i.e. if the generator field is connected across its armature) before the mechanical brakes are applied, a fairly low and consistent creep speed is obtained, and man[y] automatic skip winders obtain their stopping accuracy by thi[s] means.

The authors do not seem to agree with the French system o[f] opposing the mechanical braking torque by an electrical braking torque. It is preferable that the mechanical brakes and electrica[l] system should produce the same result independently, i.e. [a] suitable rate of retardation.

On lifts there is always a back-up protection to the contro[l] system in case of failure, and it has been the practice by law i[n] this country to fit an "automatic contrivance" which will operate in an emergency. This is different from the Continental attitude where in many cases no such back-up protection is fitted, th[e] argument being that there is nothing to go wrong with th[e] control gear. This seems rather like omitting short-circu[it] protection on an electrical circuit.

No mention is made of the smaller low-speed automati[c] winder, where successful open-loop schemes have been installed. The main consideration on any automatic winder is to obtain [a] reasonably constant and low creep speed irrespective of load, [a] top speed which will give the required performance and a smoot[h] transition between these speeds. On the smallest installation [a] 2-speed motor would probably be suitable, and any inaccuracies of stopping, if these are important or excessive, can be correcte[d] by means of an inching pushbutton.

Control from each level is regarded as impractical on mult[i-]level equipments, and it is considered better to signal to th[e] bank control point. Control should be from the cage, o[r]

* METCALF, B. L., and CUTTLE, G.: Paper No. 1481 U, April, 1953 (see 100, Part II, p. 591).

collective signal control (i.e. all upgoing and downgoing calls collected in their correct sequence) should be used for multi-level winding.

Mr. F. T. Hindley: Skip winding, with uniform loads and where decking limits of ± 9 in can be catered for, seems ideal for Ward Leonard automatic control, but not all of us have skip winding and our cages must be decked within much finer limits to allow loading and unloading of mine cars or tubs.

The difficulty is the occasional stone-laden mine car (with a load of, say, 5 tons against the normal 3 tons of coal), which may have stretched the rope 9 in or more. The cage has to be lifted on to the keps without the advantage of the descending cage which has landed on the baulks in the pit bottom.

The authors suggest a hinged platform as shown in Fig. 7, but this can be awkward if the loading angle is too great. Would not a counterweighted platform capable of supporting the cage and operated by the onsetter give an easier loading position? In effect, the descending cage would land on the platform, and after loading the bottom deck the onsetter would release the platform brake and lower the cage for top-deck loading independent of the winding engine, which would deal, as far as decking is concerned, only with the cage at the surface.

In Fig. 19, the authors compare curves of manual and automatic retardation and state, "there is no appreciable difference in decking time"; this does not appear to strengthen the case for automatic control.

I agree with the authors' suggestion of ready means for control-circuit testing and automatic indication of faults; such facilities could usefully be employed on existing winders. However, I cannot agree that the electrical staff will not be saddled with additional maintenance when the installation is automatic.

Most cage accidents due to inadvertent starting result from the onsetter signalling the cage away before his assistant is clear, and I cannot see how automatic winding would eliminate such accidents. The onsetter rarely admits his mistake and blames the signalling system; he would be just as likely to blame the automatic control. The authors go on to say that semi-automatic control by pushbutton would be safer than manual control for men winding, but I am afraid the miners would take some convincing.

Mr. J. Sykes: The authors have indicated that automatic control can be used with either a.c. or Ward Leonard winders, and Section 8 opens with the statement that the principal features of a.c. control would be generally similar to those employed on Ward Leonard control. While accepting this statement, I would mention one main difference which not only complicates the control but makes a speed reference on the closed-loop a.c. winder appear essential.

An a.c. winder, being supplied at constant voltage, can be controlled only by varying the rotor resistance. Changing the rotor resistance changes the electrical-mechanical time-constant of the machine, i.e. the time it takes to change from one rope speed to another for a given change in rotor resistance depends on the valve of the rotor resistance. For the high rotor resistances generally necessary for low speeds under power, the effective time-constant may be 20 sec or more. This means that to change the speed from, say, 2 to 1 ft/sec would take 1 min. These speed changes occur when the conveyance approaches the landing, and response times of 1 min are undesirable.

The variation in electrical-mechanical time-constant is an essential difference between Ward Leonard and a.c. winders. With a Ward Leonard winder this time-constant is of the order of 1 sec and does not change with speed.

To overcome the disadvantages of the large time-constant a closed-loop scheme is essential. It is only with such a scheme that forcing can be employed to reduce the effective system time-constant to a value below any of the individual time-constants. When a liquid controller is used, forcing will take the form of overshoot of the steady-state electrode position. If this overshoot is too great, the winder motor might pull out, which means that the forcing available is limited by the pull-out torque of the winder motor. To prevent pull-out overriding torque, limit control should be adopted.

Another feature which makes an a.c. winder compare unfavourably with Ward Leonard is the change-over from power to dynamic braking. The minimum power available with an a.c. winder depends on the maximum rotor resistance, and in general this limits minimum power to 20% of the full-load value. The next step in change-over from power to dynamic braking is no power, and this is followed by a minimum value of dynamic braking torque. Although the minimum torque available under power is limited by rotor resistance, the dynamic braking torque can be reduced to lower values than this. This is necessary when requiring change-over to dynamic braking with light load at high speeds. The only way of doing this is to reduce the flux level at which the machine is running, thereby obtaining lower torques for a given rotor resistance and a given speed. The only way to reduce the flux level of an induction motor under dynamic braking is to use a closed-loop system, because low flux levels necessitate using the so-called unstable side of the induction-motor torque/speed curves. Such a system regulates the d.c. excitation to the stator automatically to ensure that the rotor voltage, and therefore the torque for a given rotor resistance, is controlled at some predetermined level.

[The authors' reply to the above discussion will be found on page 626.]

EAST MIDLAND CENTRE, AT NOTTINGHAM, 24TH NOVEMBER, 1953

Mr. C. D. Wilkinson: The mining engineer usually asks three questions before adopting any new equipment, particularly if it is felt that it may be more complicated than that already in use:

(*a*) By how much will it increase the output?
(*b*) By how much will it reduce the cost per ton?
(*c*) Does it promote increased safety?

The authors appear to have provided satisfactory answers to all three questions, but I wonder whether things will work out as well in practice as in theory.

Dealing first with (*a*), it is stated in the paper that the more constant cycle obtained by automatic or semi-automatic control will result in greater output. This may be true of skip winding, but I am not so sure that it would be the case with multi-deck cages employing consecutive decking. At a large colliery on the Continent I found that, although the winding engine was provided with one of the best-known automatic systems, they had reverted to manual control. The reason advanced was that the use of the automatic system restricted output, but we found that with manual control the rather dubious practice of commencing to ram a car over the hinged bridging platform before the cage had come to rest was possible, while with automatic control the rams were not released until the cage was at rest.

Turning to (*b*), it seems to me that the savings accruing from the adoption of automatic winding will be the wages of the winding enginemen. At present, Regulations 65 and 66 of the

Coal Mines Act require the constant attendance of a winding engineman, so that unless an exemption from the provisions of these Regulations can be obtained the savings envisaged will not be possible. It must be made clear, however, that we have always found H.M. Inspectors and the officials of the National Union of Mineworkers very anxious to co-operate in scientific advances, so that if a sound case can be made there should be no insurmountable difficulty in amending the Regulations. The fact remains, however, that if we dispense with a number of winding enginemen and then have to take on additional maintenance electricians, the savings will be considerably reduced.

There can be no doubt that under (*c*) the use of closed-loop control and the elimination of links in the signalling-starting chain will result in increased safety. It is certain that closer "shadowing" of the engine speed throughout the wind will be possible and that risk of overwinding will be very materially reduced.

Turning now to the technique of winding, I agree that the whole problem of winding revolves round the question of the maximum size of winding rope which will operate satisfactorily and have an economic life. My opinion is that a locked-coil rope of 2¼ in diameter is the largest which can be expected to operate satisfactorily. Anticipated depths and payloads are such that this rope is too small to give a suitable factor of safety, and we are therefore forced to consider multi-rope winding and, consequently, the adoption of tower-type Koepe winders for large skip-winding plants. Cage-and-counterweight winding has definite advantages for service shafts, and we hope to have representative installations of these new types in use in the East Midlands coalfield in the near future. I feel, however, that control from the conveyance itself will be difficult, in view of the depths and winding speeds involved. Since the winding speeds are much higher than those used in lift practice, I am not sure that proximity switches would operate satisfactorily, and wonder whether the use of relays operated by radioactive isotopes has been considered.

Mr. H. Entwistle: The French winders referred to in the paper have a speed range right down to zero; the system can be left without the brakes on and yet with the power applied, and the cage will remain around one point in the shaft. Much to our surprise we found that although they were developing at the same time as ourselves, they had produced a similar system and used the same type of rotary amplifier. They had a responsible-minded market and told us that this was one of the reasons for the success in the development. The move is towards fully automatic winding, and all the post-war installations I saw use closed-loop technique with rotary amplifiers.

Regarding a.c. winders, while it is true that control can be made to give, in the main, Ward Leonard characteristics there are serious obstacles. There are, of necessity, discontinuities in the characteristics, such as the abrupt changeover from power to braking, so that a high-performance closed-loop system may be used, but there is a short period during which there is no control on the machine at all. Where the load torque changes from positive to negative, closed-loop control may change the machine over to braking, but if this causes deceleration an immediate switch back to power may be necessary. This form of hunting is not conducive to long contact life; therefore a greater speed tolerance may have to be accepted.

The tendency in this country has been towards the use of a.c. winders, chiefly, I fear, on account of first cost, although in many cases they are a sound economic proposition. On the Continent, when we ask why Ward Leonard winders are almost universal, they reply that "they are so safe and easy to control; the winder is the most important item at a pit, and if winding is not carried out efficiently it is the whole pit which is slowed down; the pits should have the best winding equipment available." It is true that the a.c. winder can, by the addition of dynamic braking and complicated control, be made to give convenient overall characteristics, including automatic slowing down after a primary trip, but I feel that Ward Leonard control, having the right characteristics fundamentally, will always be ahead and will become more popular. Why is it that there has been so little desire in this country to make the Ward Leonard winder popular, especially for automatic winders?

Mr. G. S. Hyson: What is the maximum voltage advisable for the winding motors using the Ward Leonard system?

What is the maximum speed the authors would recommend for the motor-generator equipment?

With a Koepe winder using overturning skip and counterweight, the weight ratio with a loaded skip is approximately 2 : 1½ in favour of the skip, but after the skip has reached the surface and discharged its load the weight ratio is 1½ : 1 in favour of the counterweight. Therefore with the skip in the overturned position, some difficulty will be experienced in bringing the skip back into the shaft into its normal position without slip occurring between the ropes and the Koepe sheath. Would the authors indicate their recommendations to avoid slip taking place under these conditions?

Messrs. N. R. D. Gurney, G. H. Boden and **N. Westworth** also contributed to the discussion at Nottingham.

[The authors' reply to the above discussion will be found on page 626.]

NORTH STAFFORDSHIRE SUB-CENTRE, AT STOKE-ON-TRENT, 27TH NOVEMBER, 1953

Mr. G. E. Woodliff: There are two other methods of unloading cages which have not been mentioned by the authors but are worthy of consideration, since they enable a considerable reduction in the decking period to be achieved:

(*a*) The use of balance cages: with this method all decks are unloaded simultaneously, the tubs being transferred to the balance cages, and while the next wind is proceeding the tubs are unloaded from the balance cage, this being decked consecutively.

(*b*) The use of cages fitted with tilting floors: with this method the mine car and floor tilt, enabling the load to be discharged without actual handling of the mine car. This method combines the advantages of skip and cage winding, enabling decking times akin to skip winding to be achieved with a similar reduction in handling; the conveyance can still be utilized for men and material winding.

With regard to supervisory control (Section 5.1), I am unable to agree that method (*b*) is confusing to the driver, since at all times the linear relationship between lever position and speed is maintained over the actual speed range as determined by the cam gear. With method (*c*) this relationship is changed by the cam gear, and if the driver selects a creep speed in mid-wind he must alter the position of the lever as the conveyance approaches bank to maintain this creep speed.

Dealing with the provision of acceleration and retardation control, the requirement is for overriding acceleration and retardation limitation. This is achieved in a similar manner to current limitation by comparing a signal proportional to acceleration (or retardation) with a reference signal, a signal being fed into the amplifier only if the former exceeds the latter.

I understand that Continental manufacturers experience trouble with mechanically operated shaft limit-switches, and

there is no doubt that there is a real need for something on the lines of a proximity switch. I believe that the lift-type switch originally called the Pliotron depends on two mutually coupled inductors, one in the anode circuit and the other in the grid circuit of a valve oscillator. The oscillations cease when the vane is inserted between the coils. However, the clearances involved tend to rule out the use of this device for mine winders.

[The authors' reply to the above discussion will be found on page 626.]

RUGBY SUB-CENTRE, AT RUGBY, 2ND DECEMBER, 1953

Mr. T. J. F. Oldham: The statement in Section 7.5 that decking is within $\pm\frac{1}{2}$ in on automatic winding requires clarification, and I suggest that, on automatic winding, the out-of-balance load raised was always the same; hence this accuracy may be a tribute to the consistency of performance of load measurement, speed control and the operation of limit switches and mechanical brake; with greater consistency in these factors, the error may approach zero. Such is not the case shown in Fig. 17, where extremes of unbalanced loads are shown. The error in Fig. 17 is ± 7 in (or $\pm 10 \cdot 5$ in without the balance rope), and it may be noted that the levelling speeds are of the same order in the two cases. In Fig. 17 no load/speed compensation appears to be used. In lift work, such compensation is essential, and levelling speeds of $0 \cdot 3$–$0 \cdot 4$ ft/sec must be obtained to give stops within $\pm\frac{1}{2}$ in over the whole range of unbalanced loads.

However, Fig. 20 shows definite reversal of motion prior to stopping, suggesting that a level-correcting device is also used. This reversal appears both when lowering a load and raising it. Thus the final stop is effected from some speed which is probably less than 3 ft/sec, owing to the short accelerating distance during relevelling. Will the authors give some particulars of the method employed for level stopping?

It would seem that the performance shown in Fig. 17 might be greatly improved by two features commonly used in lift practice, namely

(*a*) Series turns, giving resistive compensation, on the Ward Leonard generator.
(*b*) Refraining from opening the armature circuit when applying the mechanical brake.

Such an arrangement needs careful design and initial adjustment and the use of a "suicide" circuit during standstill. The remaining difficulty, residual magnetism, is not easy to eliminate, and it seems that it is for the levelling-speed condition that the closed-loop control is most needed, since it provides consistent levelling speeds without special design and manufacture. The response time should be made short, to suit the levelling condition.

There appears to be some discrepancy between Figs. 15 and 17. Fig. 17 shows a rise in speed following the action of the stop switch at 0 when an out-of-balance load is being lowered. Such a re-acceleration corresponds with the expression "cuts off power" in Section 4. Admittedly, acceleration would occur, owing to gravity, with an a.c. motor drive, between the cutting-off of power and the mechanical braking. I understand that generally in Ward Leonard winders the armature circuit is not opened, and therefore power is not cut off.

Fig. 15 shows positive excitation for all loads, and hence disconnecting the supply from the generator field at point 0 in Fig. 17 would produce electrical braking immediately and so prevent re-acceleration; the effect of mechanical braking, if sufficiently powerful, may later produce a pulse of accelerating torque, but this can only reduce the momentary value of retardation.

From Fig. 12 it seems that about 20 sec of cycle time might be saved by simultaneous transfer of cars from the cage to a slow-speed 3-deck lift, which could be made to level itself automatically to the winder cage and then to discharge the cars to bank whilst the winder was running another trip. The winding capacity would be considerably increased, while the decking accuracy of the winder need not be critical.

Finally, in passenger-lift practice the speed control has long been vested in the apparatus, leaving the driver to make a minimum of decisions and to put them into effect by a simple movement. Control switches often have a single contact, used to start the machine in a predetermined direction, stopping being entirely automatic and independent of the driver's foreknowledge.

Mr. W. J. Pool: To what extent is the definition of unbalanced winding given in Section 2 accepted? What term is used to describe the winding of a single cage?

In Section 7.5 it is taken for granted that high inertia is necessarily detrimental to automatic control. High inertia is certainly objectionable to the winder designer, since it increases the motor rating and power consumption; but when the motor rating has been increased it is not obvious that automatic control is rendered more difficult. The chief difficulty of automatic control is to maintain consistency, and it may be argued that inertia is a nearly constant factor, whereas the load is the variable factor. The smaller the ratio of the latter to the former, the easier it should be to produce consistent results.

[The authors' reply to the above discussion will be found on page 626.]

WESTERN CENTRE, AT CARDIFF, 14TH DECEMBER, 1953

Mr. A. W. Kidd: I note that the authors consider the use of keps without passing any opinion thereon, and it might be inferred from Fig. 11 that keps can be used, not only at pit top and pit bottom, but also at intermediate landings. The latter procedure is not permitted by the Coal Mines Act, since it would constitute a serious hazard if the keps were to be left out with a cage passing through the landing at speed. There is a growing body of opinion that keps should be eliminated altogether from winding shafts, for a surprisingly large number of winding accidents arise from their use, e.g. winding enginemen may, through faulty signalling, commence winding before the keps at pit top have been withdrawn. Slack rope develops, and if the banksman then withdraws the keps the descending cage is allowed to fall freely until it is brought up with a jerk which may be sufficient to break the rope.

There is at the moment no satisfactory governing device for mechanical brakes which will result in a constant rate of retardation, and I think that the development of such a deceleration governor should be undertaken as a matter of urgency. Until recently it has been almost universally the case that brakes have been applied by weights operating through a system of levers, and therefore the braking force has tended to be constant irrespective of requirements. There is now some trend towards the use of hydraulic or compressed-air operating gear with the weights as back-up, but I am not aware that any arrangements have yet been made for applying the brakes with a force available

to suit the momentary requirements of the winder. There are in the country certain firms specializing in the manufacture of mechanical servo and governor systems, and I think that if the problem were to be put to them a solution would probably be forthcoming.

To some extent the development of the braking gear of winders has been retarded by universal insistence that the brakes should "fail to safety," but I think the time has now come when this principle may have to be disregarded for the primary application of the brakes, provided that it holds good on the back-up arrangements.

In Section 13.2 the authors set out the procedure for automatic cage winding and state that the weight of the rope down the shaft will ensure that the winding drum turns until there is no slack rope above the top cage. It appears from this that there will certainly be slack attachments on the bottom cage, which should be avoided, otherwise when the next wind begins there will be a jerk on the rope lifting the bottom cage off the baulks. The answer may be to eliminate keps and baulks altogether, although this would involve hinged platforms for cage winding.

The authors mention winding with cage and counterweight, and I feel that in the future this system will become very much more common, because of its ability to work equally well from any number of intermediate levels in a shaft. With present methods of horizon mining, multiple levels in shafts are becoming common and are not dealt with readily by ordinary winding means unless one employs the clutched parallel-drum arrangement. If the cage-and-counterweight system is adopted using a tower Koepe with multiple ropes in parallel, possibly 4, 8, or 12, the arrangement becomes very simple and a quite small-diameter Koepe wheel can be used even with the heaviest pay loads. For instance, I have heard of one system working with 12 ropes where the pay load is 60 tons. Continental experience to date indicates that there is no great difficulty in making multiple ropes share the load. Signals would be entirely dispensed with (after all, present signals are merely a means to an end—not an end in themselves), and there would be one banksman at the pit top and one onsetter at each lever and at the shaft bottom. The conveyance would be brought in automatically to creep speed and then either allowed to come to rest also automatically or homed manually by the adjacent operator if, owing to heavy loads and great rope stretch, this would be more convenient.

Deck changing would be performed by pushbutton control, the operator having sight of the actual movement of the conveyance. With this system there will be no keps and one could possibly reach the point where even guide wheels could be dispensed with, since by selecting the correct number of ropes the Koepe-wheel diameter could be brought to the right size to allow the balance weight to hang suspended in the correct position. Naturally, fixed guides would be used, and it would be necessary to have these mounted on the sides of the conveyance rather than the ends, otherwise difficulty would be experienced at the intermediate landings.

Mr. H. M. Hughes: An effective brake governor has long been considered a desirable development. With automatic winders, such a device would have further application in maintaining constant the distance travelled after operation of the shaft stop-switch. However, governing would have to be rapid in response to be effective. For emergency operation, governed braking can be achieved with Ward Leonard winders with these schemes except in the case of power failure. With a.c. winders, it might appear that governed braking could be obtained by reducing the reference voltage at a prescribed rate. Probably, rapid changing from driving to dynamic braking would cause difficulty, owing to the rapid variation in rotor resistance required. Perhaps two sets of electrodes would provide a solution.

Advantage has been taken of torque limitation by closed-loop control for a winder conversion in this Division. The existing drum shaft is to be protected against the maximum torque that the required motor can produce.

These closed-loop control schemes make a change in the relative merits of Ward Leonard and a.c. winders. The speed of the a.c. hoist can now directly correspond to the movement of the lever. Thus, overriding speed control with cam gear can now be obtained; previously, this could only be obtained with Ward Leonard winders. With Koepe winders, detaching hooks are not used and an overriding control is required to prevent overwind at more than creeping speed. However, there can now be no objection to a.c. geared Koepe winders with manual control. This, in turn, raises the question: Can geared drives be mounted in towers? A recent investigation showed a saving of 50% of the winder capital cost by adopting a.c. geared drives instead of direct-coupled Ward Leonard control for a twin-winder Koepe tower.

The Draft Koepe Rules specify a maximum speed of 40 ft/sec for men. With Ward Leonard winders, speed limitations can be obtained by inserting (with the man-safety lever) a resistance in the generator field circuit. With a.c. winders, this could now be done by inserting a resistance in the reference-voltage circuit.

Mr. T. H. Petch: The authors very rightly advocate closed-loop control for automatic winders.

There are in South Africa and on the Copper Belt a number of Ward Leonard winders working quite successfully on automatic—or rather semi-automatic—winding with open-loop control. A casual visit to the engine-house will find the driver sitting back from the controls or even turned away from them and yet the winding engine is carrying on perfectly satisfactorily with its job. These winders are thoroughly satisfactory when winding a constant load for a fixed distance at a constant speed. These conditions must, however, be maintained, and this is where the limitations of this type of winder are apparent.

I went into one winder house and while watching the equipment from the platform asked the driver if he could reduce the speed while on automatic winding by bringing his control lever towards neutral (it was in the full-speed position). He replied that he could and proceeded to demonstrate and speed was accordingly reduced. However, on moving the lever back to full speed again, the winder only partly picked up to speed and subsequently came to creep speed at least a drum turn before the end of the wind. The driver then had to change to manual winding just to complete that particular wind. Afterwards everything was reset and continued as normal. The normal accuracy of decking with this winder was about 6 in. In all cases, overturning skips are used.

In the second instance the winder is required to operate from two depths, namely 1 600 and 2 400 ft. It is, moreover, driven by a flywheel motor-generator set, so that there is considerable variation of generator conditions during the wind, because of the reduction of the motor-generator speed during this time. This winder, if set to deck accurately for the 2 400 ft depth, will when changed to the 1 600 ft depth, deck only within 18 in of the original setting. This, however, is not an inconvenience with the skip-tipping arrangements which exist at this mine, and can be tolerated.

The third instance is of a new equipment with was probably not yet properly adjusted because it had not been running for more than a week or two. It was supplied from a motor-generator set without a flywheel, so that generator speeds were reasonably constant throughout the wind. While the equipment behaved perfectly satisfactory for one direction of wind with a decking accuracy of up to, say, 6 in, on the other direction of wind it was, on some journeys, coming to a creep speed a full drum

turn before the final stopping position, and was in consequence wasting a lot of time. The driver's explanation was that the skip on that side was not being filled properly.

I watched the master controllers on all these equipments, and in each case the controller arm was brought suddenly to neutral a full five seconds before the winder came finally to rest.

I think the limitations of open-loop control will be apparent from the foregoing instances, and it will be evident that automatic winding is then dependent on an exact repetition of conditions, cycle after cycle. Closed-loop control is not dependent on an exact repetition of conditions, and the accuracy of decking can be maintained no matter how the cycle of events has been disturbed. Moreover, lengthy slow-running periods can be avoided.

The question has been raised about the rope suspension on the 4-rope winder at Hanover. I have been told that this now includes C-rings in compression in the suspension of each rope and that rope suspensions are adjusted so as to obtain equal gaps in the C-rings.

Mr. D. J. Thomas also contributed to the discussion at Cardiff.

[The authors' reply to the above discussion will be found on page 626.]

NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 11TH JANUARY, 1954

Mr. T. H. Bertram: On a typical run with an automatic a.c. winder started by means of a pushbutton, the winder accelerates to full speed, runs for a given time at full speed and is then retarded by dynamic braking. When the cage is near the surface it comes in at a creep speed and finally is brought to rest about 6 in above the keps by automatic application of the mechanical brakes.

The brakes are then partially released so that the loaded cage causes the drum to slip through the brakes and land fairly gently on the keps. This is achieved by having two pistons in the brake engine, one having 75% and the other 25% of the total piston area which is hydraulically operated. The pressure is released from the larger piston, resulting in only 25% of the braking effort being exerted, and the desired results are usually obtained. There are cases, however, when the cage fails to fall back and the banksman must release the brake entirely. This is not due to light cage loading, as it occurs under varying load conditions. Can the authors suggest any means whereby this may be readily overcome?

As the law stands at the moment, the winder must be operated on manual control when winding men, and the winder is then driven by the banksman by remote control away from the winding engine, where neither the drum nor the depth indicator are visible. Materials are also wound to intermediate levels by the same method. The remote depth indicator at this control point is not sufficiently accurate in its reading to ensure that the cage is landed at the correct mark, the error being a foot or more. I feel that a vernier-type instrument should be fitted, with one pointer indicating the approximate position in the shaft and another distinctively coloured pointer revolving at drum speed for final landing. Since the driver cannot hear the sound of his engine to indicate its power or braking torque, or see his drum to indicate position, I feel that instrumentation is of vital importance.

The remote depth indicator mentioned above is driven by a Selsyn. Should the main circuit-breaker trip during a wind, the power will be cut off from the Selsyn and the indicator will come to rest immediately. The cage will then travel a certain distance before coming to rest under the action of the mechanical brakes. This puts the depth indicator out of phase, and it is necessary to wind slowly to the surface and then reset the indicator. Do the authors recommend a separate supply suitably interlocked with the main supply to feed the Selsyn?

Some years ago it was considered that the only brake on a winder should be that applied to the drum on a geared a.c. machine. It was thought that if a brake was applied elsewhere, such as on the high-speed shaft, the gearing might be overstressed during emergency conditions. With automatic winding, retardation is carried out by dynamic braking at the motor and the retarding forces are transmitted through gears and shafting. It is therefore essential to have adequate strength in the transmission to withstand the forces set up, which take the form of a sudden stress reversal. While the dynamic braking force is controlled to a certain extent, I feel that due allowance should be made in the design.

The automatic electric winder has several complicated circuits, and in the event of a shutdown, some time may elapse before a fault is located and rectified, with considerable loss of output. It is very desirable to have a fault relay cabinet installed, so that when a fault develops there is an immediate indication of the circuit involved.

Mr. E. le L. Lamb: Underground arrangements generally will need a great deal of improvement before any inefficiency in the shaft will even be noticed. When what may be termed the mining side of the organization can guarantee a continual supply of minerals at the shaft bottom through the shift, then will be the time to look for the last 1% in efficiency of winding.

An order has just been placed in this district for a small automatic staple winder operating with single cage and balance rope, and in view of the authors' mention of control from the cage, it is interesting to note that in this district again serious consideration is at present being given to the installation of an auxiliary Koepe winder for men and materials, to operate from 550 ft with single cage and balance weight, with the operator travelling in the cage. No technical difficulty is expected, and the general impression is that the trouble will be to get the removal of restrictions—both statutory and otherwise.

Mr. N. S. Walker: For the purpose of loading and unloading suspended cages, the authors have proposed the installation of platforms. In the North Eastern Division, at Cadeby Main, Maltby Main and Thurcroft Collieries, there was installed a type of simultaneous banking gear which was arranged for loading and unloading cages supported on keps at the surface and on sump baulks at the pit bottom and which included four independently operated auxiliary cages adjacent to the main cages.

The operation of the auxiliary cages and the decking operation was controlled by one man at the surface and another at the pit bottom. At Cadeby Main Colliery the full tubs at the surface and the empty tubs at the pit bottom were discharged automatically by gravity from the auxiliary cages at the banking and onsetting levels respectively. The empty tubs and the full tubs entered the auxiliary cages at those levels also. The average decking time was 8 sec. On the surface at Maltby Main Colliery, no labour was required for handling the tubs on the pit bank, except at the tipplers. The empty-side auxiliary cage took care of the difference in level required for gravity operation of the tubs. At Thurcroft Colliery, devices were provided for ensuring proper sequence of operations. Would it serve any useful purpose for consideration to be given to the possibility of simultaneously loading and unloading the decks of suspended cages by associating platforms with this type of simultaneous banking gear?

Mr. G. A. Jackson also contributed to the discussion at Newcastle upon Tyne.

[The authors' reply to the above discussion will be found on page 626.]

SHEFFIELD SUB-CENTRE AT SHEFFIELD, 17TH FEBRUARY, 1954

Mr. G. E. Woodliff: Certain Electricity Boards, and in particular the one in the Sheffield area, are very concerned about the effect of a.c. winders on the supply system; it has been suggested that the rate of rise of load should not exceed 1 000 kVA in $\frac{1}{8}$ sec. Is this purely a local problem, or do the suthors consider that it will preclude the use of automatic a.c. winders on a large scale?

I consider that the speed/load characteristics obtained with the 2 500 h.p. Ward Leonard equipment are surprisingly good. Is the generator provided with a differential series winding, which is often considered desirable to limit the circulating current under certain suicide conditions? The provision of this feature usually means that the speed/load characteristic is not very good. For example, it can result in a drop of generator voltage of $8\frac{1}{2}\%$ from no load to full load.

The speed-measuring device for a Ward Leonard equipment need not necessarily be a tacho-generator. In fact, the use of a tacho-generator introduces errors due to brush-drop, residual effect, etc., and tacho-generator also has certain other undesirable features. The winder-motor e.m.f. accurately represents the speed, and this can be derived by taking the generator voltage and adding a signal proportional to motor *IR* drop. This method obviates the necessity for a tacho-generator—an additional rotating machine—and is common practice in America.

American practice is to rely on current limitation rather than acceleration control. The Americans provide acceleration control but set it for a high but safe rate of acceleration. They make the current limit very sensitive by providing a second amplifier, and by these means work the machines up to their maximum peak of twice full load; since acceleration control is not completely overriding, this reduces the winding times with light load. This is the very opposite of graded acceleration, the current falling rapidly at the end of the acceleration period. It will be noted that with the French winders the loop current tends to fall after about two-thirds of the acceleration period. Thus the maximum overload capacity of the machine is not utilized.

Is this gradual decay of current considered desirable, or should steps be taken in the design of the closed-loop system to maintain the forcing effect on the amplifier up to the end of the acceleration period, thus maintaining constant acceleration for a longer time, resulting in a reduction in winding time but with consequent high peaks on the supply system?

With regard to cage-controlled service winders, I consider that the best solution is not to use trailing cables, which have rather an unhealthy record, even on lifts, but to mount the push buttons at the level so that they can be operated by the driver from within the cage. Do the authors consider that the Inspectorate will insist on an emergency stop-button within the cage, thus compelling the use of trailing cables?

In practice, the design of a winder closed-loop system is based on the fact that sudden load changes only occur owing to changes in acceleration of the winder. Other load changes, such as those due to skip dumping, etc., are generally slow. The usual type of servo does not deal very adequately with sudden load changes at constant speed; for example, 2% full speed. I believe that this type of load change is not met in practice, but would like confirmation of this.

[The authors' reply to the above discussion will be found on page 626.]

MERSEY AND NORTH WALES CENTRE, AT CHESTER, 15TH NOVEMBER, 1954

Mr. W. E. Mangnall: The method of performance or the technique of winding is laid down in broad outline in the paper, from which can be calculated, built up or assembled all detail work. This detail work, I should imagine, is the problem given to the manufacturers by the authors. One might say in passing that with the resources they have at their disposal these obligations can probably be fulfilled.

The components which make the whole of automatic winding must of necessity be reliable, they must be continuous in operation and if there is any failure they must of necessity fail to safety. In mentioning reliability I ally with it a regular and conscientious system of maintenance. Electricians will have to maintain these automatic winders, and it must of necessity be incumbent upon them to add to their knowledge, and it would assist them perhaps if in the build-up of the control of automatic winders we could get down to a basic standard of control. It may mean a pooling of ideas of manufacturers, and that may not seem as silly as it sounds, because it has already been done with several other items of plant in common use in the mines of Great Britain. In order to obtain what has been put forward, it seems to me that it can only be done, not necessarily by trial and error, but by experimentation in the field, preferably at collieries where alternative means are provided for winding the mineral which would be otherwise be lost due to any failure of the automatic winder installed. This may take years to reach finality, because it is a long time since the first automatic winder was installed in this country.

The authors state, quite rightly, that automatic winding should take into consideration also the transportation of coal to the shaft at the bottom, its discharge at the top and its conveyance to wherever it has to go. These two items should be taken as an integral part of the operation. In the concentration of output of large shafts or major reconstructions, there may be a case for automatic winding. Where maximum shaft utilization is by means of perhaps two winders, one can be automatic and deal with the coal and the other can be manual and deal with anything else. There are a number of shafts in Great Britain, perhaps a thousand, that are just ordinary coal-winding shafts. Have the authors worked out any exercise to show whether, at an ordinary shaft, automatic winding compared with the manual operation or the existing steam winder is economical? If one approaches the Area General Manager on any project he will say, "How much will it cost, do we save any men, shall I get more coal, shall I get more coal per man, shall I get it up to the surface at a certain rate?"—and the engineer must justify the position before he can embark on any programme of change-over of winders, costing many thousands of pounds. What would be the expected minimum percentage saving for the capital outlay required to justify automatic winding? Again, will the cost of the services of the winding enginemen be replaced by oilers, greasers and electricians that are so necessary to maintain it?

Mr. G. Nicholls: The paper is provocative and is obviously intended to be a challenge to the engineers in the industry and to the manufacturers, and from that point of view it must do good. Questions will be asked, and no doubt already have been asked, first of all with regard to safety. We are all striving for improvements in safety technique in winding work, and if automatic winding can give us greater safety we should have it; but we are installing electric winders now in the confident hope that the controls already applied to these winders are giving a much greater degree of safety than the steam winder. Is the degree of safety provided with automatic control of a modern

electric winder greater than with hand control of the same machine? Surely the position with hand control is that any failure on the part of the engineman would be a failure to safety.

We believe steam winders are things of the past and the sooner they go the better. There are 12 winders in N. Wales and three of these are already converted to electric drive. We shall be converting another 4 and shall be installing one new electric winder as well in the next 2 years—that gives 8 out of a total of 13—and we shall probably be converting three of the others in the near future. We find that the overall efficiency of the electric winder is very much higher than that of the steam winder.

I have no fears about the alterations in the Regulations. No developments would take place at all if we held back because it might be necessary to alter the law. If the Ministry is convinced that new methods might lead to greater safety it is very willing to secure changes in the statute.

The authors mention what seem to be rather low rope speeds. They quote a winder with a maximum winding speed of 42 ft/sec. In this part of the country we are winding at 60, 70, 80 and even up to 90 ft/sec.

They also refer to a number of accidents which have occurred in winding in the last 12 or 13 years. How many of these have occurred with electric winders?

Mr. D. B. Russell: The authors mention the difficulty in obtaining accurate decking when winding varying loads automatically, and for this reason suggest that in such cases Ward Leonard control should be used in preference to a.c. drive. While agreeing that this problem is more difficult with a.c. winders than with Ward Leonard control, I do not think we should exclude them on this score alone, since the problem is not insoluble. Have any practical tests been made with the combined mechanical and d.c. dynamic braking scheme described in the paper?

Although automatic winding of men is not at present allowed, some increase in safety can be obtained by adopting supervisory control. If and when automatic winding of men is permitted, there would not seem to be much point in providing supervisory control for the odd occasion when a wind has to be carried out manually. Any winder incorporating automatic or supervisory control should be provided with an easy and rapid change-over to the basic open-loop control, so that no winding time would be lost should a fault develop in the speed/load compensating circuit.

With automatic operation, I feel strongly that there should be only one stopping operation per wind. With multi-deck cages this implies simultaneous decking, and I would be interested in the authors' views on this.

Mr. J. B. Lancaster: Several speakers appear to be worried that the programme will only result in the present winder operating staff being replaced by maintenance staff. General experience in industry suggests that this is not likely to happen, as it is more usually the case that a several-fold economy in man-power can be achieved by a mechanization programme such as this.

Mr. P. H. Harvey: It would be interesting to know how much the mining industry in this country intends to follow lift practice when considering the design of automatic winders. Lifts, to get their stopping accuracy, use rigid guides. The coal-mining industry prefers rope guides, and it can be imagined how difficult the stopping problem is if a cage swinging from side to side is guided only by ropes suspended in a shaft. Far greater accuracy of stopping would be obtained with rigid guides, particularly at mid-shaft levels.

One of the lantern slides showed a man underground controlling the destination of a cage from inside, and it would be of interest to know the method of storing calls from intermediate levels. In a 5-storey building it is exasperating for someone on the third storey to see the lift passing between the first and the top storeys without stopping. In such a case an automatic call system is required to store all calls; otherwise an improperly designed automatic winder or lift could waste a lot of time for those on intermediate levels, as they may never have access to it.

Another point which is brought out is the expectation of great accuracy from closed-loop control, but no mention is made of the accuracy which can be obtained. For instance, Fig. 15 shows the best that can be done on open-loop control on a Ward Leonard winder without any corrective devices for differences in loads in the conveyance. What are the equivalent figures for a Ward Leonard winder at the maximum and minimum speeds when fitted with closed-loop control?

In Fig. 17, the curves for stopping accuracy are based purely on theory, whereas that in Fig. 20 is based on practice. In fact, open-loop-controlled automatic winders give substantially the same result as shown in Fig. 20, owing to the effect of electrical "suicide" and mechanical braking taking place simultaneously. Some skip-winding installations fitted with open-loop control and load measuring are capable of being stopped within a few inches whether at no load or full load.

On one of the lantern slides, a single lever was shown for operating the brakes and controlling the speed. While this has long been the practice for controlling the speed and brakes of cranes, it has not yet found favour, except on the smallest equipments, on electric winders in Britain and most other countries.

Mr. E. Marshall: For a number of years in the 1920's I had considerable experience of a Ward Leonard set, and the small amount of maintenance required was astonishing. I have seen what has happened and heard some of the remarks on the amount of maintenance needed on some straight a.c. winders which have been recently installed. Does the Rototrol method of winding, which was installed in South Yorkshire recently, compare with the Ward Leonard method?

Mr. E. P. Hill: In the d.c. winder (Ward Leonard), the first fundamental difficulty is due to the hysteresis loop of the generator. The fact that the generator covers a range from almost zero to full voltage, both forward and reverse, means that, owing to the traverse of a family of hysteresis loops, the excitation field current differs for the same generator voltage, depending on previous excitations. This necessitates correction by the control apparatus, or different motor speeds will result for similar controller points owing to changes in residual and hysteresis effects.

The second fundamental difficulty is the speed/load regulation. The IR drop in the main electrical machines is of the order of 3% at full load current, i.e. 3% of normal voltage. If, then, the generator is only at half normal voltage, the load regulation is 6% in voltage at full load current. Consequently the motor speed regulation at low voltages and speeds becomes comparatively large and the speed has to be corrected to normal by the control apparatus. By the use of modern high-speed cross-field excitation systems on the closed-loop method, such difficulties have been successfully overcome in other fields of application such as rolling-mill drives. The chief difficulty in connection with high-speed control is stability, since hunting can develop when high amplification factors are adopted. It would have been of interest to have details of control excitation schemes which have proved reliable and successful in service with the cases mentioned. The use of a winding on the main field of the generator to give a signal proportional to $d\phi/dt$ and hence to dV/dt, and so to rate of change of motor speed, is a well-known device. Although it is

not an accurate measure, it may be more desirable than very-high-amplification separate-speed-acceleration measuring devices. The working cycle of a winder is slow compared with that of a rolling-mill, and therefore there should not be any insuperable difficulty in the design or operation of automatic systems to the requirements described in the paper.

Some easing of the control-excitation difficulties which ari would be obtained at additional cost to the main generators reducing the *IR* drop to a minimum, by compensation of t generator and motor, by lamination of fields, etc.

Mr. Ayton and **Mr. H. G. Jones** also contributed to t discussion at Chester.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. B. L. Metcalf and **G. Cuttle** (*in reply*): During the latter meetings and discussions, mention has been made of the tower-mounted multi-rope friction winder, the development of which has reached its culmination since our paper was first presented. This is likely to be the type of winding plant generally to be adopted for new installations and will have far-reaching effect on winding technique. It is therefore necessary in summing up the discussions to consider its effect on automatic control. The friction winder operates on the Koepe principle, but instead of a single rope, two or more ropes—usually four—are used. These pass over a drum fitted with friction grooves and are attached to two conveyances, or to a single conveyance and a counterweight.

(*a*) Keps are not used—their elimination has constantly bee advocated during discussions.

(*b*) The winding system is balanced, and a power diagram a shown in Fig. 2 of the paper is obtained. The payload and spee can often be so selected that the power diagram is positive througho the wind.

(*c*) Where widely varying loads and both raising and lowerin are to be catered for, as in service shafts, the single-cage-and-counte weight system will normally be used. With this system the counte weight is usually made equal to the weight of the conveyance, plu half the load—and the net out-of-balance load is a smaller pe centage of the total mass of the system than obtains with tw conveyances winding; hence, variations in payload and the differenc between raising and lowering have less effect on speed and deckin accuracy.

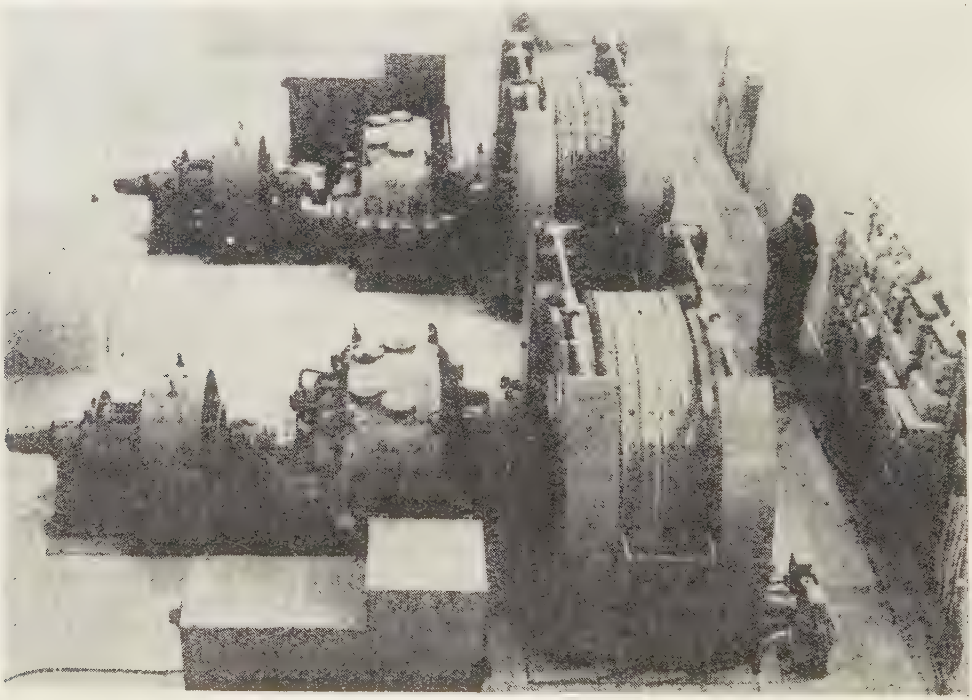

Fig. H

Balance ropes are used to equalize the system. A typical multi-rope winder is illustrated in Fig. H.

For single-level winding the practice will generally continue to be the winding of two conveyances in balance, but where multi-level winding is to be catered for, the single-cage-and-counterweight system, as used on lifts, will be adopted. This eliminates the difficulties envisaged in Section 13.2.1 of providing for automatic control with clutched-drum winders. To obtain an equivalent output at the same winding speed, with the single-cage-and-counterweight system, the payload must be double that required for two cages, and hitherto its use has been limited by payload restrictions imposed by single ropes.

Friction winding simplifies the problems of automatic control for the following reasons:

Several speakers have outlined the difficulties of achieving really precise automatic control with a.c. winders, rightly drawing attention to the fact that the electrical and mechanical time-constant of the equipment, on which the stability and degree of response depend, are higher than on Ward Leonard equipment. There are also mechanical problems in the automatic operation of large liquid controllers and, where fixed resistors are used, of accommodating them and dissipating heat. Therefore it would appear that for the time being the practical application of automatic control of a.c. winders may be limited to equipments of a maximum of about 2 500 h.p. depending on the controller dissipating capacity required, and to skip and single-deck cage installations on which no deck-changing operation is involved.

A.C. winders are driven through a reduction gear, but where Ward Leonard equipments are installed they can either be direct-coupled or geared. The arrangement of the drive should be as compact as possible and should permit of slight variations in alignment between the drum and driving unit due to possible deflections of the main supporting beams in the tower. Where direct-coupled motors are used they should preferably be of the overhung armature type. The motor-generator set can either be mounted in the tower—if space permits—or at ground level. In the latter case it is desirable for the direct voltage to be as high as possible, in order to keep to a minimum the size of the cables between the generators and winder motors. The voltage is limited by the voltage per bar permissible on the commutator: 560 volts is normally used, but it would be an advantage if this could be increased to 1 500 volts. A speed of 750 r.p.m. is generally considered a desirable maximum for the motor-generator set.

We have carefully reviewed the points made by speakers about methods of control and consider that, for mineral winding, control could be by pushbutton, but for men winding and for special duties, supervisory manual control should be provided at the surface landing place. With tower-mounted winders these controls cannot be "direct-connected" as illustrated in Fig. 23 of the paper, and a means of remote operation is necessary. It would be well, therefore, also to provide simple direct emergency manual controls at the winder, preferably with a means of cutting out all automatic features.

Owing to the accuracy which can be achieved with closed-loop control, any attempt by the driver to apply the mechanical brake—unless the electrical control lever is in the "off" position or the power supply has been cut off—will result in the motor driving through the brake, because the equipment will endeavour to maintain a speed proportional to the position of the control lever. Simplified manual control can be achieved by a single lever which actuates both the electrical control and the brakes.

Where such control is installed, the operation is virtually the same as for pushbuttons. On the driver moving the control lever away from the "off" position, the mechanical brake is automatically released when sufficient torque has been built up; the winder then accelerates under control of the acceleration or torque-limit control to a speed proportional to the position of the control lever. To retard the winder, the driver moves his lever back towards the "off" position. This causes the winder to retard due to electrical braking at a rate proportional to the rate of movement of the control lever, up to a limit determined by the setting of the retardation control reference. When the controller is put to the "off" position a mechanical brake is applied either (*a*) when the speed of the winder is reduced to a creep; or (*b*) immediately the lever is put to the "off" position when mechanical braking would be superimposed on electrical, and the retardation produced would be controlled to that determined by the setting of the retardation reference.

Where remote control is adopted, a remote depth indicator should be provided at the landing place. This could be Selsyn operated, but precautions must be taken against power failure to the Selsyn which would result in the indicator getting out of phase with the conveyance. The equipment should therefore be so arranged that in this event an emergency trip is initiated, and when the safety circuit is reset and the power restored the winder can only be operated at reduced speed until the conveyance is brought to the surface and the indicator is synchronized. A speed indicator should also be provided.

On remote manual control the speed of the winder should automatically be reduced to a creep at the ends of the wind. With the cage-and-counterweight system, if it is required also automatically to reduce the speed approaching a selected level, it would be necessary for the driver to operate a selector switch.

Where pushbutton control from the landing place is adopted with the single conveyance and counterweight system, the pushbutton stations should be located at each landing level in the case of cages, and at the loading and despatching position in the case of skips. The control of the shaft should be exercised from the surface landing, from where provision should be made for despatching the conveyance to any selected level in the shaft. On arrival it should be possible to effect control from that level only for the purpose of loading, discharging and despatching to the surface, unless a release key has been operated which would enable the conveyance to be controlled from the surface either to despatch it to another level or to call it back to the surface.

If in special cases provision is to be made for winding continuously between levels in the shaft, means should be afforded whereby the banksman can transfer control to the uppermost level.

Where balanced conveyances are used, the winder would be controlled from a pushbutton station at the surface. With regard to control underground the onsetter could signal to the surface landing in the normal way when he had completed his loading operation and was ready for the cage to move, or he could press a button operating a switch in the winder starting circuit which would be complementary to the pressing of the button at the surface to start the winder, in which case the pressing of the button underground should be visually indicated at the surface landing.

Where pushbutton control is provided from the cage with a cage attendant in control, as in lift practice, there should be a selector switch at each of the landing places for the purpose of selecting the level to which it is intended to travel. A mechanical means should be provided to operate, from one deck within the cage, a starting switch mounted in the shaft. This should be so arranged that it cannot be operated unless the cage gate is closed, and that the operating mechanism cannot strike the switches mounted in the shaft at intermediate levels if the operating mechanism is inadvertently operated whilst the cage is in motion in the shaft. The shaft gates should be so interlocked with the winder starting circuit that the winder cannot be started unless the shaft gates are closed. Control of deck changing and loading at various levels would be the responsibility of the cage attendant. For this purpose, pushbuttons for control of deck changing should be added at each level. These should be so arranged that they can be operated only by a key carried by the cage attendant. A means of communication from the cage to the surface should be provided.

Where provision is made for persons to ride the shaft at will, controlling the winder from within the cage as in a lift, the controls provided should be the same as for the control with a cage attendant, but in addition a release key and call buttons would be necessary at each level, so that if all persons leave the cage at a level the release key can be operated, which will permit the cage to be called to any level, provided that the shaft gates are closed. A suitable means of discrimination in the control system is necessary in a multi-level shaft, to determine in which direction the cage must travel when a call button is pressed.

A normal signalling system, separate from the pushbutton control system, should be provided, interconnecting the pit bottom, insets, surface landing and direct manual control station generally as follows:

(*a*) *Direct manual control* from the winder-room landing would require the normal signals between underground levels, the surface landing and winder room.

(*b*) *Remote manual control* from the surface landing would require signals between underground levels and the surface landing.

(*c*) *Pushbutton control from the surface landing with two cages* would require signals between underground levels and the surface landing.

(*d*) *Pushbutton control from the landing places with cage and counterweight* would require signals between underground levels and the surface landing for men winding. With an onsetter on duty at each level there would be no need for signals for coal winding, but telephonic communication between the surface and each level would be necessary.

(*e*) *Pushbutton control from the cage* would require no signals, but a means of communication from the cage would be necessary.

On a friction winder a certain amount of rope creep takes place on the friction drum; this means that the conveyance can get out of phase with the depth-indicating, controlling and protective devices; it is therefore necessary to provide a creep-compensating device, to synchronize these devices automatically with the cage position. This should operate at the most frequently used level—usually the surface.

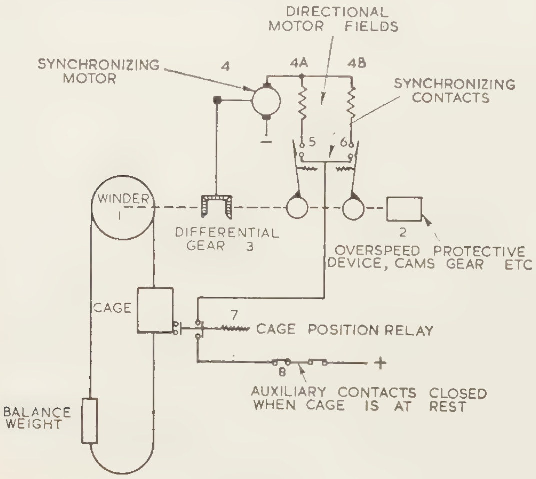

Fig. J

The essential features of a creep-compensating device are illustrated in Fig. J. If the conveyance is stopped at the level at which synchronizing is effected, and if the protective and controlling devices are exactly in phase with the conveyance position, contacts 5 and 6 are open. If, however, synchronis[m] has been disturbed, one or other of contacts 5 or 6 is close[d] depending on whether the winder is advanced or retarde[d] relative to the conveyance position. The closing of contac[ts] 5 or 6 energizes the motor to drive the protective and co[n]trolling devices in the proper direction to bring them into corre[ct] relationship with the conveyance.

The motor can be operated only when the conveyance is i[n] the synchronizing position; i.e. contact 7 is closed by the magn[et] on the conveyance and contacts 8 are closed by the hoist bei[ng] at rest.

Where automatic pushbutton or remote manual controls a[re] installed, in addition to the safeguards outlined in Section 1[.] it is necessary that the following additional safeguards b[e] provided:

(i) The mechanical brake should be so interlocked that the pow[er] is cut off from the winder motor and the emergency brake applie[d] if the brake is not fully released within a limited time after th[e] controls have been operated to start the winder.

(ii) Where pushbutton control is provided, equipment should b[e] so arranged that for an emergency trip the winder must be operate[d] manually at a limited speed until the cage has been brought to th[e] surface and the cause of the stoppage ascertained.

(iii) On manual control, when men are being wound, the sha[ft] gates should be so interlocked with the brake lever that an alar[m] is given at the landing place if the shaft gates are opened unless th[e] winder brake is "on"; and, once applied, the brake cannot b[e] released until the gates are again closed. On pushbutton contr[ol] the shaft gates should be interlocked with the winder startin[g] arrangements so that the winder cannot be started unless they ar[e] closed.

(iv) If a descending conveyance becomes jammed in the guide[s] the load on the ropes may be relieved and the winder continu[es] to rotate, the ropes slipping on the drum. Where winders ar[e] operated remotely either manually or by pushbutton, a devic[e] should be fitted to stop the winder if this occurs. This could consis[t] of centrifugally operated switches—one driven from the winde[r] drum and the other from a pulley driven by the winding rope, an[d] so connected that, should the winder continue to run after th[e] rope has stopped, the power is cut off and the emergency brake i[s] applied.

It is regretted that space precludes a more detailed reply t[o] the many questions which have been asked during the dis[-]cussions, which have been most valuable and constructive. I[t] is encouraging that since the paper was first presented severa[l] automatic installations have been planned.

DISCUSSION ON
"METER PROBLEMS AND CONSUMERS' LOAD CHARACTERISTICS"*

NORTH MIDLAND CENTRE, AT LEEDS, 24TH NOVEMBER, 1953, SOUTHERN CENTRE, AT HOVE, 2ND MARCH, 1955

Mr. J. L. Ineson (*at Leeds*): My first point refers to Table 1, n which saturation factors are given for cooking, water heating nd space heating. If, with the exception of space heating, hese are applied to the average consumption given in Table 2 f the paper by Schiller† we reach an average annual consumption f, at the most, 1000kWh. This is very much less than the gure of 2250kWh given in Table 1, and leaves a large con-umption unaccounted for. It would appear, therefore, that he sample includes a large amount of space-heating load and, or that reason, it is a biased sample. In comparison with he more normal consumers who have less space heating I magine that it will contain too large a proportion of consumers vith large meter sizes, and it would seem that the result will have een to increase the proportion in the under 10% load range in Table 3.

My second point refers to the footnote to Section 8.2.1, where t is stated that "The statistical confidence limits for the actual igure of 12·6% are 10·6–15·4% with a 10% probability of xcess." Why are the limits not symmetrical about 12·6%, and vhat is the real meaning of the footnote? Does the mean lie etween these limits with 90% probability or do 10% of the ases in the sample fall outside these limits? Does the 10% robability really refer to *excess* above 15·4%?

My third point refers to Figs. 4, 5 and 6. By implication Fig. 6 follows from Fig. 5, but if the sloping line at the top ight-hand corner of Fig. 5 is converted to the basis used in Fig. 6, the result is a curved line (part of a parabola) between 0 and 80amp load. This is perhaps not particularly important, ince, if we take Fig. 6 as the correct basis, i.e. if the potential lemand remains constant between 40 and 80amp, and convert his horizontal line to the basis of Figs. 4 and 5, the result is a urved line at the top right-hand corner of Fig. 4 which, ortunately, lies above all the points on the scatter diagram.

The fourth point relates to Section 2.3 in which the authors efer to the economic requirements for fixing the proper servicing eriod. This is stated to be such "that the annual net losses of evenue owing to increasing minus errors, together with the cost f servicing, should be a minimum." In spite of what the uthors have stated, I am still not convinced that metering errors ose revenue for the supply authority. When there is a loss in evenue the tariffs are revised to stabilize the financial position. Moreover, the readings of the meters, whatever they record, are sed in fixing the tariffs themselves. Of course, if the minus rrors could be avoided more revenue would result from applying he tariffs, but on the other hand, if minus errors had been nissing originally, the tariffs would have been fixed at a lower evel. Therefore, while I agree that it is worth while ascertaining he value of the losses, I feel that the authors have given the wrong xcuse for so doing. The correction of meter errors ensures nly that one consumer is not prejudiced relative to another, nd it is therefore necessary to determine how large one can llow the discrepancies between meters to become before relations with consumers will be made difficult. This is a much harder criterion to fix and satisfy than that put forward by the authors.

Mr. H. J. Sheppard (*at Leeds*): The paper deals with two problems—the selection of the size of meter to be installed at any given consumer's premises and the period for which a meter should remain in service before being removed for cleaning and retesting. The formula proposed in Section 8.1 for determining the size of meter results in the selection of a 10amp (m.c.r.) meter for any domestic consumer having an installed load up to and including 2·4kVA at 240 volts and a 40amp (m.c.r.) meter for a consumer having a load exceeding 2·4kVA but not exceeding 19·2kVA at the same voltage. The practical situation is slightly more complicated owing to the need to re-use meters manufactured in accordance with earlier editions of B.S. 37.

I believe that, with increasing development and the facilities for the use of electricity now being provided in the majority of new dwellings, there can be few houses for which one can state definitely that the installed load is not likely to exceed 2·4kVA within the service period of meters now being installed, and I think that the 40amp rating could well be adopted as a general standard for all new meters to be connected in domestic premises. This would still leave a large number of earlier meters of lower maximum continuous rating for use as replacement meters in the minority of existing consumers' premises where the load appears likely to remain small.

Mr. J. L. Ferns (*at Leeds*): Whilst the point made in the third paragraph of Section 2.2 has a logical flavour I am afraid it would not lead to a good law. The authors appear to have overlooked the relationship of the meter error to the immediate consumer concerned. They will be well aware that in the course of its on-circuit life a meter may serve a number of consumers. Thus, although a meter might have a total life error within the legal limits, the error for the last consumer might be outside those limits. Furthermore, when a complaint comes before a meter examiner the question at issue is surely the state of the meter at the time and not the nebulous figure of its life error.

On the question of choice of meter the authors have dealt only with the relation between the changing meter error and consumers' load characteristics, but surely there are other economic factors of importance. These are as follows:

(i) The purchasing of a standard quarterly meter results in a considerable easement of the work and costs of a meter department.

(ii) The use of a standard size of meter eases the work of the consumers' records office as well as the work of the meter fixers and the installation inspectors.

(iii) The use of a standard size of meter, which is capable of meeting the load of any ordinary domestic consumer, saves any future worry as to meter capacity. This point is important because few consumers observe the ruling that extensions of load must be notified.

(iv) There is little point in the sales staff encouraging the use of heavy-current appliances if meters have to be changed before they can be used. In this connection it must be observed that it is uneconomic to change a meter before it has served its useful certified life. Since a quarterly meter has a useful life of over ten years, it is evident that it would take a very clever forecaster to estimate the load which may eventually arise in a particular residence within that period.

* Golds, L. B. S., and Schiller, P.: Paper No. 1483 M, April, 1953 (see **100**, art II, p. 619).

† Schiller, P.: "Operational Research in Electricity Distribution and Utilization rogress Review)," *Proceedings I.E.E.*, Paper No. 1133, July, 1951 (see **98**, Part I, 229).

In view of these considerations I believe that the choice of meter size may be governed by certain basic facts which would override any scientific facts which might be forthcoming from the investigations described by the authors.

It seems, therefore, that the greatest merit of the authors' investigations is the decision that a more accurate determination should be made of the period which should be allowed to elapse before a meter is brought in for repair and recertification. It seems also that the period might be controlled more by departure from the legal limits than by the attainment of a life error within the legal limits.

I am disappointed that the motive behind the authors' enthusiastic and scientific approach to the problem appears to be due to a decision that little hope exists for a solution to meter-bearing deterioration. This is a pity because obviously there would be no problem if the twentieth-load errors of 20 or 25 amp meters were reasonably stable over a period of years.

Mr. G. H. Warne (*at Leeds*): Some simple formula, as suggested in the paper, for determining the meter capacity is undoubtedly a necessity, since it is now impracticable for meter engineers to be responsible for the installation of individual domestic meters. Over-metering has always been prevalent, since the capacity is decided by an installation inspector or meter fixer who tends to install large meters owing to failure to appreciate diversity, over-emphasis of safety and the tendency to avoid further changes. This will only be overcome by adequate tuition of those responsible.

I support the author's suggestion that legal tolerances should be based on the actual total consumption registered. Since the introduction of the 1936 Electricity Supply (Meters) Act, it has been obvious to meter engineers that it is an impracticable requirement for a meter to be accurate within the approved limits for any load at which it may be operating. A 40 amp (m.c.r.) meter for instance, installed to register the consumption of a 7 kW electric cooker, is thus expected to register accurately on a 40-watt lamp (1/240th load).

Reference is made in the Introduction to the great difference between the standard of maintenance prior to and after nationalization. I suggest that greater variations were to be found prior to the implementation of the Electricity Supply (Meters) Act, 1936.

What do the authors consider to be the accuracy of the indications—and of the demand period—of the thermal-demand indicators utilized? I should be glad if the authors would elaborate the suggestion in Section 8.1 that the thermal maximum demand would appear likely to exceed the corresponding sustained demand by a good margin.

The authors have indicated the biased nature of the sample, and although all such information is undoubtedly of value, I feel that too many conclusions have been drawn from too small a sample, which in itself is not representative of conditions in the country as a whole. A considerable amount of further sampling in different areas is obviously necessary before these conclusions can be accepted.

It appears that 30% of the meters sampled were calibrated over 14 years ago, and were thus uncertified, and that 10% were over 20 years old and thus probably of doubtful design. The results given in Table 7, therefore, might be considered reasonable, but it is to be hoped that they are not representative, especially in areas where the certification programme has been completed.

The conclusions from Fig. 7 would appear only to confirm that all meters should be calibrated to their best possible accuracy curve having regard to testing costs. The "margin for additional load" referred to in Section 3.3 might reasonably be accepted to cover the connection of a cooker or wash-boiler, and thus we return to the installation of a standard 40 amp (m.c.r.) meter.

Mr. S. F. Musson (*at Leeds*): In Section 3.3 the autho[rs] deprecate the practice of standardizing on a meter with a certa[in] current rating, and no doubt refer to the 25 amp long-range (l.[r.]) meter which was for many years in general use for domes[tic] supplies.

The sample tests they have taken do show a certain amou[nt] of over-metering, but in their anxiety to correct this state [of] affairs they recommend sizes of meters which may give rise [to] the conditions of under-metering. In Table 1 they refer to [a] saturation factor of 22% for cooking, but in some areas th[is] figure has been greatly exceeded, reaching a value of 35%, [so] that it is necessary to exercise care in the choice of meter size. The present 40 amp (m.c.r.) meters are often the equivalent [of] 13 amp (l.r.) meters, and it is by no means certain that the use [of] what in comparison are smaller meters will ensure longer li[fe,] sustained accuracy and stability at lower loads. Factors su[ch] as greater speeds, cycles of heating over a greater range [of] temperatures affecting the "breathing," the oiling of bearing[s,] insulation and the protective coatings of the various meta[ls] must all be taken into consideration.

Although the authors mainly discuss one economic factor [in] their approach to the problem of obtaining accurate meters, i[.e.] the cost of periodically servicing existing types, it may also [be] possible to obtain better types of meter at a greater initial co[st] which would be offset by lower maintenance cost.

As the authors rightly state, the economics of metering a[re] complex, and I feel that they have tried to consider the equi[ty] of the position between the vendors and the users of electrici[ty] in a reasonable manner. The purists, on the one hand, requi[re] meters to register to within very narrow limits of accuracy, s[ay] $\pm 1\%$, whereas at the other end of the scale we have those wh[o] say that electricity should be sold under conditions which do n[ot] require the use of meters. I feel that the consensus of opinio[n] is definitely in line with the present legal limits, but to mainta[in] meters within these limits, a high standard of knowledge [is] required both with regard to the correct selection of sizes as we[ll] as methods of maintenance.

Mr. A. C. Bailey (*at Leeds*): Domestic-consumer load chara[c]teristics have more variables than the paper would suggest.

Take, for instance, a sample of houses costing between £6[00] and £800 at pre-war prices. Many have water heaters or cooke[rs] and many have both, and space heating is very variable, as a[re] the habits of the consumers. In addition, there is anoth[er] variable, since space heating depends on the consumers' co[al] stocks. With council houses, either pre-fabricated or site-buil[t,] there is probably not the same variation, except that there [is] a vast difference between the two types, bearing in mind th[at] many prefabricated houses are "all electric."

Regarding the method of sampling mentioned in Section [...] I think that an unrealistic answer would be obtained if certa[in] domestic consumers were included. I know of an instance—n[ot] a very large house—where there is a 36 kW circulator install[ed] and only about 4 kW of other apparatus.

The fourth paragraph of the Summary gives the answer as [to] the size of meter to use. This is obtained not from informatio[n] supplied from operational research, but on the score of the lar[ge] useful range of the modern meter.

I am glad to see the suggested rewording of part of the Electr[icity] Supply (Meters) Act, 1937, in Section 2.2, and I would go furth[er] and state that the accuracy is related to the prescribed workin[g] range of the meter. It is unfair to expect a meter to be accura[te] with only the load of an electric clock, which is inferred in th[e] present wording.

Section 3.3 is vague, since no time is stated in regard to th[e]

over-current. We should accept only the value in B.S. 37. Many makers are giving an overload value in excess of the specification, but this is not in the spirit of maximum continuous rating, and probably affects the lower end of the curve.

The load-analysing meter described has given invaluable information in the research, but I have no faith in the maximum-demand information obtained. The response to a domestic-load curve is very variable. I do not think that maximum demands are maintained for longer than 20 min, as stated in the paper—at least it is not my experience after perusing many current charts.

Were any difficulties raised by consumers during the yearly meter tests? I have encountered many consumers who thought that the only purpose in carrying out site tests was to advance the meter index or at least to speed up the meter.

The scatter in Fig. 4 rather illustrates my remarks about maximum-demand readings and also has a bearing on the apparatus as distinct from the installed load in amperes.

Referring to Table 3, I should like to know the actual consumption under the several headings.

Mr. J. T. Scott (*at Leeds*): If we accept the fact that the information about consumers' load characteristics is only in the nature of a pilot survey, have the authors considered the possibility of altering the load analysing meters in order to obtain more information in the range 25–100% of meter rating, perhaps at the expense of information for over 100% rating? From Section 2.3 it would seem to be the authors' ideal to replace only those meters which are found after a period of years to have negative errors. I suggest that the main consideration is not the average error of the group of meters being considered but the spread of the errors. In any case, however, if a limitation of the period of validity of certification is introduced, the economic basis for a proper service period will not need to be considered.

Mr. J. M. Vanderleck (*Canada: communicated*): The economic basis of the paper is that losses of revenue together with the cost of servicing meters should be reduced to a minimum. The basis is questionable if it is admitted that loss of revenue does not represent expenditure of national effort, because it may be overcome either by increasing the rates or by initially adjusting meters to be fast, so that on the average they are correct during a service period. It follows that if legally the meter must be accurate to within certain limits throughout its service period, the most economical meter is the one which will remain within legal limits the longest without any servicing.

The Dominion Government of Canada specifies the maximum allowable limits of error, and also the maximum allowable period of service, which is generally 8 years for new meters. If all new meters remain within legal limits throughout an 8-year service period, and if loss of revenue owing to increasing minus errors can be overcome by initial adjustment of accuracy or rates, the most economic meter is the one in which the monetary loss owing to failures in service, plus the cost of periodic servicing every 8 years, is a minimum.

The authors ignore the usual item "fixed charges," which appears in most economic studies. Presumably this can be neglected only when the purchase costs of the different meters are the same. Also ignored is any consideration of the amount which can be justifiably spent to reduce the deviation of meter error from the average. So long as the deviations from the average do not cause errors outside the legal limits, there may be no incentive to the undertaking to obtain further reduction. However, the average consumer may be willing to spend a certain amount to reduce deviations, with the object of increasing the probability that his consumption is measured within limits of say $\pm 3\%$.

In the Hydro-Electric Power Commission of Ontario, a preliminary study of the characteristics of consumers' loads metered with single-phase watt-hour meters indicated that possibly 12% of the total energy is delivered when the load does not exceed 500 watts, which is about 9% of the nominal rating of the 25 amp 230-volt 3-wire meter. Less than 1% was delivered at loads exceeding 6000 watts, which is about the full load on this meter. This is evidence of over-metering, which indicates a requirement for high accuracy at light loads.

To improve metering, the Commission has recently established standard ratings for all 60 c/s services (excluding those of most municipalities) as follows: for 115-volt 20 amp services, the standard meter has a maximum continuous rating of 30 amp, and is accurate to within $\pm 2\%$ from 0·5 to 30 amp. For 115/230-volt 35 amp and 50 amp services, the standard meter has a maximum continuous rating of 60 amp, and is accurate to within $\pm 2\%$ from 1·0 to 60 amp. For services in excess of 60 amp capacity, combination energy-demand meters will be used. Data obtained through the use of load-analysing meters should enable lost revenue and accuracy of measurement of the total consumption of individual consumers to be calculated, for standard meters of different makes and characteristics. For initial investigations two special load-analysing meters are being used, which together provide load bands as follows: 0–10 watts, 10–20 watts, 20–50 watts, 50–240 watts, 240–600 watts, 600–2400 watts, and all over 2400 watts. This will enable the importance of accuracy at light loads to be determined.

Mr. R. W. Langley (*at Hove*): The authors' aim is to find the solution to two problems which have been outstanding for a number of years. These are (*a*) choosing the best size of meter for a particular installation, and (*b*) deciding on the interval between overhaul and retesting.

The first requirement is difficult unless a meter is available which will register accurately for a prolonged period over a very wide range, and it was my impression that B.S. 37: 1952 was intended to overcome this problem. The authors have shown that, from tests taken, the 40 amp meter is somewhat large for present-day loads, particularly in the north of England, since the largest percentage of registration is in fact on the lower loads. They have painted a somewhat sombre picture of great losses owing to under-registration as the meter gets older. However, I suggest that within the life of the present-day 40 amp meter the sub-range of registration will increase to a figure very much higher than those obtained in tests made up to the present. It is, of course, impossible to predict this figure, but it is not unreasonable to imagine that it will be three or four times its present figure for the lower examples and may be 1·5 to 2 times the value for the higher figures. Electricity will undoubtedly be used on an ever-increasing scale in preference to other forms of power, and its use for water-heating and cooking will doubtless become universal.

At present the costs are to some degree pegged to those of coal, but there is evidence to show that this state of affairs is likely to change in the not-too-distant future, and unless means are provided for synthesizing gas, or some other alternative means for supplying the same needs is available, the price of electricity will not increase at the same rate as the present alternatives.

Fig. B shows the variation of price with time. I have purposely not included any date, since quite naturally this is somewhat impossible to predict, but I suggest that a period of 20 years would not be unreasonable. This trend will therefore have a three-fold effect, namely:

(i) It will cause more people to change to electricity for all forms of domestic lighting and heating requirements.

(ii) It will increase the sub-range at which the present meters show their maximum registration.

(iii) It will reduce the overall effect to the consumer of a small error in the meter registration.

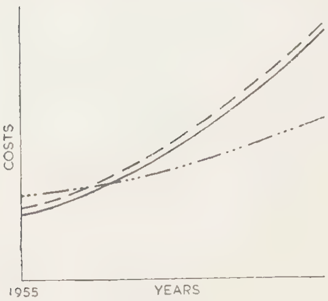

Fig. B
Coal.
Gas.
Electricity.

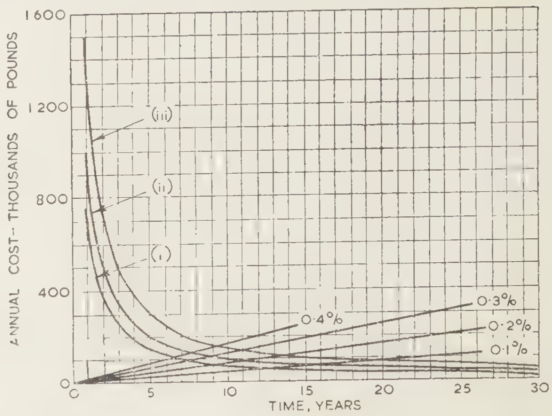

Fig. C
(i) 15s. per meter.
(ii) £1 per meter.
(iii) £1 10s. per meter.

These three factors will tend to allow the period between successive overhauls to be increased, since the authors have stated that the maximum error tends to occur at the lower end of the scale, i.e. on lighter loads. I therefore suggest that in the first instance the 40 amp meter is not too large to handle the present and future requirements and that, subject to experience with the modern meter to the requirements of B.S. 37, the period between overhauls may well be extended to 20 years. Thus, if we assume its life to be 40 years, it will have one major overhaul during that period.

With regard to the meters now on circuit which are 10, 20 or 30 years old, and of which there are some 16 million, how can we decide the period between overhauls? The authors have suggested various methods, each of which in their separate ways have certain merits, but none of which, in itself, is entirely satisfactory owing to the wide variation which occurs between consumers' loads and demand factors. Furthermore, the characteristics of the large number of different makes and types are not all the same. If it were possible to assess the situation with a large enough sample we should doubtless find that some types would require overhaul much more frequently than others.

From the point of view of legislation, should we suggest that the period between overhauls be based on the worst—or the best—or some value in between? A middle course would naturally be chosen since it would be impracticable to assess the various types and allocate different periods for each. From experience so far gained it is evident that 10 years is too short a period for the great majority of meters and that 20 years is perhaps too long. A middle course is therefore suggested, and 15 years would seem to be a good average.

With regard to the economic period between overhauls, there are two basic factors: (*a*) the cost of repairs and overhaul, and (*b*) the cost of under-registration.

(*a*) is a function of the operational costs of labour and test-room facilities, etc. (*b*) is a function of the rate of growth of error in the meter. The interval will therefore depend upon the balance between these two factors. When the annual cost of repairs equals the annual under-registration, from an economic point of view the meter should be overhauled. Fig. C shows curves representing the annual costs for overhauling a million meters, for different periods between overhauls, based on 15s., £1 and £1 10s. per meter. Superimposed on these curves are the annual costs of under-registration with the same number of meters for a cumulative annual error of 0·1, 0·2, 0·3 and 0·4%, each meter being used for registering 1 000 kWh/annum at 1d./kWh.

It will be seen that, if the average annual cumulative error is 0·1%, the annual loss of revenue will equal the annual cost of overhaul after 12 years' service when the overhaul cost per meter is 15s., 15 years for £1 and 19 years for £1 10s. When the average error is 0·2% the periods become 9, 11 and 14 years respectively. This is on the assumption that at the time of installation all meters are neither fast nor slow.

As the authors have stated, from a legal point of view, a maximum error range of 2½% fast and 3½% slow is permissible, and provided that all meters operate within this range, it is reasonable to assume that the consumers and the Area Board will be satisfied. I therefore suggest that, in order to extend the time interval between overhauls and thus provide a saving which will be passed on to the consumer, the meters start their life with a positive error. It can be shown that an initial error of +1·5% can increase the time interval between overhauls by some 5 or 6 years with an attendant saving.

It is in the interests of all concerned that more thought be given to techniques for obtaining long-term stability, both on the part of the manufacturers in their initial design and also in our own test rooms when overhauls are being carried out.

Messrs. L. B. S. Golds and **P. Schiller** (*in reply*): We reply to the points raised by individual speakers under separate headings.

Mr. Ineson.—That the sample is biased in comparison with average national conditions, and that this is mainly in respect of space heating, is shown by the average installed space-heating load of 2·3 kW per consumer, as compared with a national average of about 1·5 kW. The confidence limits stated in the footnote to Section 8.2.1 are not symmetrical about 12·6% because for the size of sample in question the distribution is not symmetrical. The footnote would have been clearer if the words "of these limits" had been added. We are grateful to the speaker for pointing out an over-simplification in Fig. 6, which, however, does not affect the argument.

If the theory was applied that the tariff should be revised when the revenue does not come up to expectations owing to the under-registration of the meters, it would appear to the consumer as a higher charge for the service because of the acceptance by both consumer and supplier of the kilowatt-hour as the standard for measurement of electrical energy. The consumer would not be aware that the higher price was due to under-registration, and therefore he would tend to restrict consumption. In practice, we are considering an average error of the order of 5% or less of the true consumption. The charges are not, however, adjusted to such close limits, the minimum step being 0·1d. per kilowatt-hour, so that progressive adjustment of the kilowatt-hour charge to cover inaccurate metering, even if it were known and tolerated, is not feasible, and some other indirect method would have to be employed.

Progressive under-registration is, in fact, occurring at the present time, as shown in Figs. 1(*a*) and 1(*b*). However, owing to the rapid expansion of the industry in this country, the effect of under-registration of existing consumers' meters is masked by the correct registration of new meters for new consumers connected to the system. It follows that new consumers are being penalized owing to the correct registration of their meters.

Thus we can only conclude that the proper servicing period is that stated in Section 2.3, and that it is necessary to establish the extent of the revenue losses due to under-registration—at any rate for the reasons given by the speaker.

Mr. Sheppard.—The formula proposed in Section 8.1 can be applied to any meter if its maximum continuous rating is used, which for older meters may be 125% or 200% of the rating given on the name plate.

Mr. Ferns.—The speaker appreciates the logic of the method suggested in the paper of stating the statutory tolerances. It was not the intention that the statutory limits of accuracy should be stated in relation to the whole service life of the meter, but in relation to a period, e.g. that which would be covered by an account.

We agree that a meter with a rating suitable for universal use is highly desirable, and no doubt with more knowledge about consumers' load characteristics, in conjunction with improvement in meter design, such standardization may eventually be achieved.

We believe that the speaker overlooks two facts. One is that additional load will be evident by increased consumption sufficient at any rate to indicate that a change of meter is necessary, and the other and more important fact is that the thermal capacity of meters is much in excess of their rated current for periods of half an hour or more.

Mr. Warne.—The phrase "margin for additional load" was qualified in Section 3.3 by the words "where the existing connected load is low," and thus we do not necessarily "return to the installation of a standard 40 amp (m.c.r.) meter."

Mr. Musson.—The results of tests on the meters in the sample which, in our opinion, had been correctly rated, did not show any deterioration of accuracy. It would be desirable if more reliable data could be obtained regarding the accuracy of a meter after a term of service, provided that its initial condition is known. The suggestion regarding the use of a better type of meter to obtain a longer period of service is very good, but it is necessary to know at what portion of the load range the best accuracy is required, otherwise any additional effort in producing a better meter in some respect may be misapplied.

If Fig. 7 is examined with the frequency-distribution curves Figs. 1(*a*) and 1(*b*), and with Fig. A of the London discussion, it is clear that there may be between 5 and 15% of meters, after ten years of service registering outside the statutory limits. These figures are also borne out by Table 7.

Mr. Bailey.—Generally, consumers are found to be co-operative. About 10% may not wish to take part in the tests, in which case another consumer is selected. The thermal-demand indicators were used as described in Section 8.2; therefore their individual accuracies are not of great importance in the problem being discussed.

Mr. Scott.—In these tests, we are mainly interested in ascertaining the consumption at the lower end of the meter range for reasons stated in the paper, and as a result of these and subsequent tests, we consider that there is no necessity to obtain information in the 25–100% range.

Reference to Figs. 1(*a*) and 1(*b*) will indicate that we are also interested in the spread (or standard deviation) of the errors, and this may well have a bearing upon the period of validity of certification. It will be seen, however, that the economic period (assuming the principles envisaged in Section 2.3 are agreed) may be less than the statutory period.

Mr. Vanderleck.—The thesis propounded in the first paragraph of the speaker's contribution is mainly dealt with in the reply to Mr. Ineson, but we would once more emphasize that the primary function of the meter is to provide a basis for the supply of electricity. On the grounds of integrity the meter must correctly register the energy taken, and thus secure the correct revenue under the tariff. Progressive under-registration of the meter must ultimately result in the supply becoming uneconomic owing to wasteful consumption. With increasing interest in tariff structure it would appear illogical to accept an inaccurate measurement of energy consumption when, for a relatively small expenditure, commercial accuracy can be obtained.

The question regarding economic accuracy for which the meter ought to be designed has been dealt with already,* but in the present circumstances it could very well be reviewed.

We note with great interest that energy-demand meters are being used to assess the rate of supply when the supplies are in excess of 60 amp capacity.

It may well be that, as a result of the tests being conducted in Canada using the load-analysing meter, the maximum period of service of 8 years can be extended. If, however, the tests show that the period is too long, at least the results of the load-analysing-meter tests will enable a better appreciation to be obtained of that part of the meter's measuring range which is of the greatest importance.

Mr. Langley.—We appreciate the speaker's optimism regarding the universal use of electricity for water heating and cooking and would like to see it justified. Since the early 1930's there has been a tendency on the part of supply engineers to install meters with ratings in amperes, on the assumption that loads were going to increase at a greater rate than has occurred in practice; as a result there appears to be a great deal of over-metering. The pilot test leads us to the conclusion that the aspect of utilization has not been fully taken into account in fixing the best standard ratings of meters in order to achieve the maximum period of service.

With regard to the meters now on circuit the investigation tends to show how they may be employed to the best advantage having regard to the fact that the thermal rating of a.c. meters is in excess of their name-plate rating, which relates to accuracy. The paper suggests an economic basis for deciding the period of servicing meters. From the point of view of meter registration remaining within the statutory limits a study of the frequency distribution of the errors of meters at the weighted average load on the meter, after certain periods of service, will show when the registration is outside the statutory limits.

The suggestion that meters should start their life with plus errors is not new, and as the speaker knows, the amount to which this can be done depends upon the characteristics and stability of the meters employed and the annual consumption of an individual consumer.

* See 1953, **100**, Part II, p. 637.

DISCUSSION ON

"TECHNICAL COLLEGES AND EDUCATION FOR THE ELECTRICAL INDUSTRY"*

Before the North-Western Centre *at* Manchester 4*th December*, 1951, *the* Southern Centre *at* Portsmouth 7*th May*, 1952, *and the* East Midland Centre *at* Loughborough, 19*th January*, 1954.

Dr. P. F. R. Venables (*at Manchester*): The author suggests that technical colleges should not provide engineering degree courses of any type, either full-time or part-time. It is very difficult to find any sound reason for this wholly exclusive recommendation. In Section 4.1 the author states that "Technical colleges are *better* suited for a different type of course," and he also mentions courses for which the technical colleges are *best* suited. The author is, in fact, stating that technical colleges are not better or best suited, but are exclusively or only suited, for courses other than degree ones. Recently in technical education we need to be defended from some of our friends who have been urging that technology should be taken from the universities. This is an absurd plea and is no better founded than the one that the author is making. Both suggestions are all against the evolution of courses in response to needs in this country, and such recommendations have a delusive simplicity.

In Section 4.1 (*d*) the author mentions that many technical colleges providing degree courses have small numbers of students. There are altogether about 220 technical institutions of one kind and another, and of these only 54 are recognized by London University for external degree work. If we assume that the author's arguments are true in part that teaching resources are being dissipated to some extent, and if the number of colleges is reduced by half to say 22, this is a very different matter from recommending that they should all be excluded, except for those cases which the author mentioned where there is a local affiliation. I am interested in this exception, because I believe that even he found it too difficult to ignore.

The author emphasizes the need for degree-course students to have an education of the whole man, then proceeds to make the same argument for all professional engineers, and finally produces the argument with which we can all agree, i.e. that students attending sandwich courses should also have an education of the whole man. It is clear that the author would wish sandwich courses to be conducted in institutions of a sufficient standard of amenities and range of work to make this education of the whole man possible. Having attained these standards within the institutions he then proposes to have the degree courses abolished, when in fact they would enjoy the same facilities and amenities!

There is a very great temptation to use an argument which is based on the best of one side, say the best of the universities, and the worst of the other side, e.g. the worst-equipped of the technical colleges which only just manages to maintain a degree course. Different comparisons could be made. For example, a number of the provincial universities have a far lower percentage of students in residence—about 15% as compared with, say, Loughborough College, which has nearly 80% of its students in residence. I deplore the mutually exclusive attitude which seems to require exclusion of one type of course from another, regardless of the needs which have given rise to them. The same argument would lead to the exclusion of all non-degree work from the universities, and thus impoverish both the universities and society by the loss of valuable diploma courses.

Mr. N. G. Treloar (*at Manchester*): The author mentions "guidance," and this is most important. It should start in the schools, where headmasters should advise boys as to whether they have a reasonable chance of entering a university, or alternatively of entering industry and obtaining their practical and technical experience in parallel.

Guidance is also necessary for those in industry in order to ensure that they tackle a course of study within their capabilities. A great deal of teaching time and space could be saved if many of those who continue to make unsuccessful attempts on the National Certificate were diverted to the City and Guilds Certificates. Mention has been made of external degree courses. While I support the full-time course, I am very doubtful of the wisdom of the part-time course. It is unreasonable to expect a man to work part-time on a course of studies which take the full-time man four years to cover. The result of continuous evening and week-end study is that unsufficient time is left for leisure, and I feel that the more valuable man in industry is one with a Higher National Certificate and a good social development. Furthermore, there are now many avenues to full-time education through scholarships designed to help those whose academic record is up to the required standard, but who, owing to economic difficulties, would not otherwise be able to obtain a degree.

In Section 3.1 reference is made to laboratory work and reports. Technical colleges should pay full attention to this section of a course and not, as has been suggested, leave the experiments to be worked in at the end of the year. In one particular case, no marking of the students' work was done until the end of the session, and marks were lost for unsatisfactory reporting which should have been corrected after the first experiment.

Mr. J. F. Yates (*at Manchester*): The author believes that technical colleges have a special sphere of their own, and appears to believe that the sandwich type of course would be particularly suitable for their engineering students. The award for the satisfactory completion of such a course would be the college diploma and, possibly, the "First Award" of the College of Technologists, suggested by the Report of the National Advisory Council on Education for Industry and Commerce.

This award could not be called a degree, because the universities would not recognize such an award except when made by a university; but the Report makes it quite clear that the award should be designed "at first level (Associate) to provide an educational qualification comparable in value to a university degree, and at the second level (Member) a qualification attainable after an advanced course of post-graduate study and/or research in a phase of technology." The Report was made after consultation with, amongst other people, ten Regional Advisory Councils for Further Education in England and Wales, and it was the opinion of the North-West Regional Committee that the First Award should permit its holder to proceed to a university in order to take a higher degree, and conversely, that the holder of a university first degree should be able to proceed to the second-level award of the major technical college. It was envisaged that there would only be a small number of major technical colleges making these awards. The Report does not

* Haslegrave, H. L.: Paper No. 1219, November, 1951 (see 99, Part I, p. 115).

include this prospective interchange, but there is no doubt that the value of the Award must hinge on this possible interchange, and industry and the students themselves will be quick to appraise it on this basis.

With reference to the suggested Higher National Certificate courses for the two kinds of technicians, I feel they should be differently named in order to avoid confusion with the generally understood Higher National Certificate in Electrical Engineering, because recognition of these suggested courses by employers and The Institution is bound to be at a different level from that of the Higher National Certificate, which provides part exemption from The Institution's Examination.

Mr. L. H. A. Carr (*at Manchester*): In Section 3 the author suggests that the future of professional education on a part-time basis is in some jeopardy. This is surely not so, since those most competent to judge appear to appreciate the advantages of the student simultaneously receiving both practical training and scientific education.

An incidental advantage of the National Certificate Courses is that, since many of the part-time teachers are engaged in industry during the day, closer contacts can be maintained between the full-time teaching staff and industry. Such contacts are of importance in keeping full-time teachers up to date. Also, as mentioned in Section 5.1, the value of research from this aspect is frequently greater than the mere worth of the particular results obtained. It is also most necessary that teachers should keep abreast of progress in their particular subjects by reading and study of current scientific literature.

In Section 3.1 the author points out the difficulty of arranging for sufficient tutorial work in the case of part-time students, but this difficulty must be overcome. Not only does the guidance of a tutor prevent much waste of time in exploring blind alleys, but it provides the opportunity for that "reaction of mind upon mind in discussion and debate," which the author in Section 1 rightly stresses as so necessary.

In Section 4.2.3 the author deprecates homework of the orthodox type, but this home study is essential. It is a well-known truism that to understand a problem fully, students must work through it for themselves, and not merely copy into a notebook figures and formulae presented to them on a blackboard.

In Section 4.2 the author puts forward for consideration a "different type of course." Does this not really amount to adverse criticism of existing university and H.N.C. courses?

The author states that one of industry's needs appears to be for engineers possessing a sound knowledge of the fundamentals of science, etc. But surely this is industry's *principal* need, and when in Section 4.2.1 he continues by stating that "the aim should be to give him sound basic knowledge that should last him all his career," is he not merely repeating the avowed intention of those existing full-time and part-time courses that lead to the educational requirements for Associate Membership of The Institution?

Mr. E. Roscoe (*at Manchester*): The author makes the point that students in technical colleges should spend a great deal more of their social life within the influence of the college itself. I strongly deprecate this suggestion. Much has been said about human relations, and one of the problems at present is that our society has gone into strata which confine themselves to their own social contacts with the result that each stratum is a complete stranger to the others.

Mr. T. McGreevy (*at Portsmouth*): In connection with sandwich schemes, the question of "thick versus thin" sandwiches is by no means easy to settle. If students are away from college for a long period, such as 12 months, considerable revision is often necessary when they resume their studies. If the alternate periods are very short, a student never develops that kind of loyalty to either his job or his college which is one of those invisible assets that count for so much in practice. In all sandwich schemes, the question of remuneration during the college period is difficult, particularly towards the end of the course when the student is an adult. I would like to see further inquiry into the two days per week, five-year type of course, and would appreciate particulars of any such courses now being held, with details of the qualification obtained at the end of such a scheme.

Air Comm. W. C. Cooper (*at Loughborough*): I am far from satisfied that the partnership of technical colleges and industry is nationally a really effective one, in spite of those provisions to which the author has referred, i.e. the fact that the majority of technical-college teachers have been trained in industry, that there is a large proportion of part-time teaching provided in technical colleges by people from industry, that there is a regular flow of part-time students from industry through the college, and that many actively engaged in industry serve on advisory committees and as members of governing bodies. I agree that all these provisions can be valuable, but suggest that they are not in themselves enough to secure, let alone maintain, a solid partnership based on factual knowledge and a real appreciation of each other's *modus operandi* and each other's current needs and problems. In these days of rapid industrial development, I stress the word *current*. I feel indeed that, far too often, such reassurances of collaboration are used as a facile excuse by those who pay lip service but little else to the conception of this partnership. Much more is needed than just these. For example, I suggest that increased staffing of technical colleges, revisions of syllabuses and adjustment of time-tabling are essential, not only for the reasons given by the author but also to provide much greater opportunity for all the teachers individually to create and develop their own personal contacts with the industries whose needs they serve; indeed, I would make it a condition of service that these teachers should spend a period of time, at least once every two years, working in, and not just observing, an industry related to those subjects which they teach. Industry, for its part, must be not only willing but really desirous of employing these men effectively, and I think that ultimately it must even go to the extent of releasing, for appreciable periods of continuous time, competent members from among its own employees for service as full-time teachers in technical colleges. In fact, a formal exchange system would have its merits.

Ideally, of course, the author is correct when he states that technical colleges should not provide engineering degree courses of any type. Sometime we may attain that ideal, but I feel that the external degree has proved to be too beneficial and too utilitarian to be thrown overboard easily. However, I am not unduly worried about this problem, since I believe that it will tend to solve itself, if only in an oblique fashion. Apart from differences of opinion on minor points, such as the inclusion of the heat engine and hydraulics in a syllabus intended to meet the needs of my own industry, I like the idea of what the author calls "a different type of course," until he details some of the ways in which he suggests that such a course might be run, i.e. some of his sandwich arrangements.

There seems to be a growing taste for the type of course which alternates somewhat protracted exclusive "study" periods with periods of almost exclusive "application." Some of the reasons given for such an approach are the difficulties of industry in releasing students for two days each week, the difficulties of the day-release student in adjusting his attitude to study, and the more effective development of a corporate spirit among the students.

Taking these three reasons alone: To the first I would answer

that such difficulties as do exist probably arise inherently in those parts of industry which still erroneously regard a student as a productive unit and not primarily as a student. On the second, I would comment that this difficulty can be much exaggerated, and in fact, I would quote from the paper, where it is stated, "It must be remembered that these students are in direct day-to-day contact with industrial applications and are thus better able than full-time students to understand the implications of the principles which they learn in their lectures." To the third, I would simply reply that any industrial organization which fails to use every means within its power to develop a corporate spirit among its own employees is denying itself one, if not the finest, incentive toward industrial efficiency, and any effort on the part of technical colleges towards the same end cannot be more than something additional. I am sincerely willing to be wholly convinced about this particular form of sandwich course, and can understand its value to those who after training will not necessarily be geared directly to the productive effort in industry. However, for those who will be so geared, i.e. the great majority of professional engineers and technicians at least in the manufacturing industries, I must underline and support the author when he states: "The closest possible linking of academic work with industrial training is necessary as well as careful and original planning of both technical and practical training." I cannot yet see that periods of absence for one month, one term, or six months at a time, from the production atmosphere and tempo can be regarded as "the closest possible linking" or likely to produce men who are as productivity-minded as those who have been in day-to-day contact with industry throughout all the years of their training.

I think the author has omitted one most important and significant educational service that technical colleges can provide for industry. There is a growing need at present, at least in the manufacturing industries, for semi-skilled operatives, i.e. men and women who have not been trained as craftsmen, to learn more than they have done in the past—which has very often been nothing—of what lies behind the operations they perform. I have in mind particularly an experiment which is taking place in a neighbouring town, with semi-skilled operatives engaged in the manufacture of plastic mouldings and in the application of anti-corrosive finishes such as electroplating and enamelling to wood and metal. A technical college is co-operating with an industry to give these people some knowledge and appreciation of the principles that underlie the processes. The industry has already found an improvement in the work of the operatives, a more intelligent approach both to the requirements and the difficulties that arise, and a lessening in the burden of supervision; all very desirable contributions not only to productivity but to the self-respect of the employees concerned.

Group Capt. E. J. Bradbury (*at Loughborough*): I am very pleased that the primary emphasis in the paper is on the necessity for any system of education to develop the whole man. The detail of individual courses can be laid down to meet individual requirements, but we must not lose sight of the absolute necessity to produce from our courses a balanced person.

When talking to our student apprentices, I sometimes think that we tend to forget what hard work is involved in the attainment of the National Certificate. The Certificate represents the be-all and end-all of their life, and the fear that they may not get it is always present. To suggest to these young men that they should widen the scope of their studies to include subjects other than those necessary technical ones would seem to them to be quite mad, and yet it has got to be done and steps must be taken to ensure the development of the whole man as well as a competent engineering technician.

The technical requirements of the National Certificate are extensive—so much so that I have the suspicion that we might get better results with fewer subjects or possibly a lower level in the examination. Whatever the solution, we must not lose sight of that contact on which the author laid primary emphasis, and we must develop a balanced personality of competent technical skill if we are to meet national requirements from the engineering industry again.

Prof. J. A. Pope (*at Loughborough*): The author states that he is not in favour of technical colleges preparing people to study for university degrees. I think he is right, but in spite of generous grants, there is a group of people who cannot afford to go to the university, since there is a means test for those who can obtain a university grant. This hits those with large families, and they must not be overlooked.

The author has stated that the function of the technical college is peculiarly its own. When I look at his course, he has exactly the same total number of hours of instruction as we have for the university full-time degree course. I imagine that the qualities of the entrants he will want for his course will be much the same as those the university is asking, although the training may be somewhat different. Therefore, I would suggest that changing the title does not solve the problem.

We must persuade schoolmasters that an industrial career is not only a good career but is of vital concern to our future existence. Free secondary-school education is now available to boys who could not previously have had this type of education, but the parents of these boys have generally had no experience in planning a child's future. They are entirely in the hands of the schoolmaster, and it is significant that only some 10% of all university entrants are trained as technologists. This is one of our big problems.

The problem of research is extremely difficult to solve. It depends not only on having people of ability, but also on creating an atmosphere in the institution itself. The technical colleges have not yet got this atmosphere, and I do not know how they are going to get it. If senior technical-college institutes were set up, it might be possible to create the right atmosphere. It is said that universities should do fundamental research and technical colleges should do applied research, but if you are doing applied research, that in itself will bring to the surface fundamental problems which will have to be solved. It is impossible to separate the two branches like that.

Prof. H. Cotton (*at Loughborough*): Education is indivisible. The young man who comes to the university is not educational raw material. He has been processed at school for three-quarters of the total time during which he is educated.

When I interview young men who come to the university, I ask them many questions, three of which are:

How good are you at mathematics?

What kind of mathematics did you do at school and what kind of science?

What kind of advice did your headmaster or teacher give you?

The answer to the first question is generally that he has done pure mathematics and not applied mathematics. He is handicapped because he has not done this.

Secondly, he has not done physics to a high standard, but he has done general science. This is inadequate for a young man who wants to be a scientist or engineer.

Thirdly, the headmaster gave no advice about how to be an electrical engineer. Headmasters often have no interest in engineering; they regard it not as a profession but a trade.

If you compare a set of old examination papers with present-day ones, they are elementary, and thus the burden on the student becomes progressively greater. Education should be an evolution, but it should be a slow evolution so that the student can keep pace with the development of his subjects.

I think the term "external degree" is somewhat unsatisfactory. suggest that the diplomas awarded would have a higher status there were external examiners. If a man has a degree it is mething which everyone can assess. If it is a diploma people ook down their noses at it." Why does a man want a degree? it for snob value or is it a very valuable asset in industry?

Dr. H. Buckingham (*at Loughborough*): In Section 8.2 a change outlook in technical colleges is demanded. I believe that rtain changes have been taking place, even since the paper was st published. One indication of this is a certain change in titude towards the provision of university degree courses. rom the majority of technical colleges a degree can only be btained under the external examination system. In covering large number of approved colleges the system inevitably volves some lack of flexibility in the content of syllabuses and measure of remoteness of control which has no counterpart in internal scheme. Moreover, the need for students to submit large number of formal laboratory reports imposes an added urden both on students and staff. Except in a very few colleges, here a widespread demand for such courses still exists, there ems good reason for the author's contention that degree urses should not be attempted.

However, it is important to remember that one outstanding enefit of the external degree system is its influence on teaching andards. A high level of instruction must be maintained if the acting examination requirements are to be met. It follows at any scheme for an alternative qualification can be successful nly if it is backed by a means of preserving the standard of the ork. Furthermore, the measures adopted for the purpose ust readily be acceptable outside, as well as inside, the technical olleges. It is probable that a careful application of the author's ggestion of appointing external examiners would meet the se, provided that a ready interchange of views were made ossible between the examiner and the college staff.

Mr. J. C. M. Sanders (*at Loughborough*): The need to build aracter into our young men, to introduce them to the humani- es, and to give them some insight into commerce and admini- ration does not appear to be in question, but the difficulty is ow to do it when they are already being crammed with technical lucation. I suggest that the time is ripe to investigate the ossibility of National Service training being modified to meet ır requirements, and at the very minimum to ensure that there no abrupt cessation of the educational programme.

Surely the best service a young technician can render the tion is to fit himself adequately for his career. In far too any cases the present form of National Service does not help m to do this. Could not The Institution Education and aining Committee investigate the whole question of further ucation during National Service in order to ensure that it unds off technical training, develops character and ability, d returns the fully qualified man to industry?

Mr. R. C. Woods (*at Loughborough*): The relative standing of degree and the diploma has been mentioned. If we neglect snob value, in industrial recruitment we look to the present putation of the school of a university or the department of the llege from which the applicant comes, in relation to the pointment to be made. A technical college which turns out en of quality need not worry about the status of its diploma.

I strongly support the plea for teaching staff to specialize, if ey wish, in grades of work. Some teachers, who are very able the higher branches, have no sympathy with the more ele- ntary stages and little or no appreciation of the difficulties of junior student. They are much more interested in things an people. Excellent as they may be to lead the more developed nd, to the less mentally agile they are a menace, for the students left without the one essential to confident work—a grasp of first principles. A much less erudite man, with a knowledge going little beyond the stage he teaches, but awake to his pupils' needs and prepared to try more than one mode of approach to get an idea accepted, is much more useful.

Mr. C. A. Brearley (*at Loughborough*): I should like to endorse the author's plea in Section 2.1 for a pruning of syllabuses. There is a tendency in some quarters to pack syllabuses in such a way as to demand from a student, for examination purposes, a mass of factual knowledge over a wide field, to the detriment of the development of habits of thought and judgment. The aim, as suggested in the chart, of age groups in which, in general, professional academic qualification should be completed by about the age of 22 years, is desirable. In the early years of his adult life an engineer, like other citizens, should be free to devote his leisure to advancing his knowledge in his own sphere of work, clear of the incubus of examinations, and to participate in the domestic, civic and religious obligations and the pleasures of his environment.

Referring to Section 5.1, most of us need only recall inspiring teachers of our schooldays to counter the statement that research is essential to "live" teaching. It is more important for a teacher to try to keep abreast of engineering progress over as wide a range as possible than to undertake research in a limited direction; it is an advantage, of course, if the time and facilities for research are available.

Dr. D. A. Jones (*at Loughborough*): In the paper it is inferred that the university or technical college is not greatly concerned over the student being given a sound practical training. If the college took an interest in the works training, would not a certain continuity of education be obtained? After all, apprenticeship is part of the education of an engineer.

The scheme could possibly be effected by the industrial concern sending a quarterly report to the university or college on the progress of the student. In return, the college could reply with comments derived from experience of the student over the previous three or four years.

Dr. Gibbs *et al.** stated that the Higher National Certificate student takes longer than a graduate to develop into a useful engineer. There are obviously many possible reasons for this slower development, but it does seem that greater emphasis could be placed on the facilities for the social and athletic activities of the H.N.C. student. In this way he acquires the ability to communicate his newly gained knowledge and to absorb new ideas by social intercourse.

Mr. E. Houghton (*at Loughborough*): The yearly intake into a technical college embraces a wide field, from the man running his own radio shop, through the large manufacturers and nationalized industries, to every non-electrical industry which employs electrical staff. The college prospectus offers a range of courses calculated to meet this diverse demand with economic classes. Many syllabuses of national examinations have been framed by trade advisory committees, who are often more concerned with what ought to be included than with what can be assimilated in a limited part-time attendance. Anybody who has attended the enrolment at a large college will know how little time is available for individual attention to each student. The teaching weeks before the examinations are limited, and any attempt at grading in the early part of the course, with consequent upheaval in the days or evenings chosen for attendance, is fraught with difficulties.

Many embark on the wrong course, and many fall by the wayside. At present youths are in short supply, and an increase in the number of State scholarships has still further restricted

* GIBBS, W. J., EDMUNDSON, D., DIMMICK, R. G. A., and LUCAS, G. S. C.: "Post-Graduate Activities in Electrical Engineering," *Proceedings I.E.E.*, Paper No. 1265. February, 1952 (99, Part I, p. 161).

the numbers available for apprenticeships. Industry cannot afford this wastage.

I ask for two things. First, from those concerned, either through trade association or by academic position, with framing courses, let us remember that every school leaver is not from the fifth form of a grammar school in the pre General Certificate of Education era, and that there are late developers who will be able to move from one course to another. Let craft, technician and professional courses dovetail one into another, so that a person with outstanding results in a technicians' course does not have to start right at the bottom of a professional course. Secondly, I ask employers and training officers concerned with apprentice selection to include in their selection tests an attainment test, which will ensure that the selected candidates can benefit from a chosen technical course. I would be happy if, like the university matriculation, there were agreed school-leaving standards, although as a citizen I would object to any formal labelling. Any technical college would, however, be only too glad to supply suitable sample papers to employers, and would welcome any pre-testing and block enrolment. These considerations apply to apprenticeships designed to reach H.N.C. level in, say, four or five years, with exemption from the early years of the course on account of the G.C.E. (which is still a very variable standard), and they also apply to specialized craft courses where the student's early interest is obtained by specialist practical instruction and where a general pre-senior course would stifle interest and progress. Normal entry to National Certificate courses through suitable pre-senior courses does afford an opportunity for selection. However, care must be taken with these, lest through absence of laboratory work or guidance from engineering teachers the adolescent falls away, because the essential connection between course and work is missing.

Finally, I would reiterate the great need for all members of The Institution to keep in touch with schools, school-leavers and parents to advertise the opportunities in engineering and to ensure that, in competition with all careers, we in the electrical industry get our fair share of the best possible boys.

Messrs. R. F. Marshall, F. W. Taylor and **F. G. Copland** also contributed to the discussion at Manchester, and **Messrs. O. S. Woods, G. E. Smith** and **B. Gill** also contributed to the discussion at Loughborough.

Dr. H. L. Haslegrave (*in reply*): Whilst it was emphasized in the discussions that the need for the interchange of staffs of technical colleges and industry is even greater now than it was some years ago, it must be realized that the difficulties of effecting this interchange have also been increased by the rapid industrial development. It is not likely, for instance, that a teacher can go into any works and immediately justify the payment of a salary equivalent to his teaching salary. Neither can an industrial executive settle down immediately to full-time teaching work. Three ways of making the interchange of staff possible and valuable are worth mentioning.

The practice exists in a few colleges of allowing some staff to spend a half day, or more, each week in a works, at first observing and later actually participating in the work. Current developments and current problems are thus effectively brought into the college, and the transition to the teacher going on to the pay roll of the works for an extended period is facilitated. For some sections of the teaching work it is better that a teacher should leave his college and go for an appreciable time—two years or more—into industry. It is now possible for pension rights to be safeguarded in such cases, but the teacher concerned would normally desire to return to a higher-status post in his original, or another, college.

In a few colleges teachers are allowed to carry out consultati[ng] or investigating work for industry, which keeps them in clo[se] touch with industrial conditions and so makes transference [to] full-time work in industry comparatively easily possible. Th[is] practice could well be extended.

The third way, operating for at least one university, is t[he] scheme of a group of students spending some weeks in a[n] industrial concern, and carrying out some project under t[he] guidance and with the aid of members of the university sta[ff]. Such staff acquire a good and close relationship with t[he] concern.

One cannot leave this problem of ensuring that teaching sta[ff] have a good knowledge, as well as experience, of industri[al] conditions, without mentioning that the tendency of compani[es] to compete with each other for the recruitment of graduates b[y] offering increasingly higher salaries for post-graduate apprentic[e]ships is making it more and more difficult for colleges to obta[in] suitable staff. Colleges often require a man to have had [at] least two years' training and experience in industry after gradu[a]tion from a full-time course or sandwich course before taki[ng] up an assistant lecturership, and yet that man may have receiv[ed] during his practical training a salary equivalent to, or great[er] than, the maximum salary he would receive as an assista[nt] lecturer after twelve years of teaching. If such men can on[ly] be recruited at the lectureship grade, the standard of teaching [in] both assistant and lectureship grades will fall. Thus industr[y,] by increasing the financial incentives it is offering to graduate[s,] is making it very difficult for colleges to supply the required ty[pe] of man.

Several speakers stressed that colleges should develop m[en] with balanced personalities, but perhaps those who gui[de] industry and the professional engineering bodies do not appr[e]ciate fully that, as they increase the technical attainments requir[ed] of students on completion of their college courses, they make [it] increasingly difficult for time to be given to the development [of] personalities. The plea made in the paper, and justifyi[ng] repetition, is that, after taking into account National Servi[ce] requirements, there is a definite limit to the time that can [be] spent on training, and a suitable proportion of this time shou[ld] be given to the development of personality. It is possible f[or] the student to attain only a certain standard of technical abili[ty] and knowledge by using the remainder of the time, and if indust[ry] or the professional engineering bodies require a higher standar[d] it should be secured by means of post-graduate study.

In the comments made during the discussions upon t[he] proposals contained in the paper for sandwich courses, there wa[s] evident some misunderstanding of three of the essential poin[ts] in such courses:

(*a*) By incorporating in the courses extended periods [of] attendance at the college (longer than two days per week), f[ull] corporate college life is made possible, and becomes an integ[ral] part of the course.

(*b*) Close correlation of principles and practice becom[es] possible through partnership of teaching staff and the personn[el] in industry responsible for the training of the apprentice, [in] both the planning and the operating of the works training, a[nd] through the teachers contacting the apprentices in the works.

(*c*) Production consciousness is retained throughout the co[m]plete period of training.

The title and status of the award was naturally referred [to] frequently, but this problem appears nearer solution now than [at] the time of the discussions.

Recruitment of students was touched upon by many speake[rs] in two of its aspects—recruitment to the individually appropria[te]

pe of course, and recruitment to the engineering industry. ne first aspect involves not only the planning of the various ourses, but the giving of the best advice to students and, in eir early years, their parents, by college staff and industrial aff, and it also requires the readiness of education authorities make financial grants to students taking sandwich courses. ome authorities have become more generous in this last respect uring the two years 1953–54, but many still award grants nly for degree courses. Whilst a main purpose of sandwich ourses is to provide a fuller training than through the medium of art-time day courses, they are also likely to attract into them, nd thus to the engineering industry, students who would not ave considered going to a university and who might have ought another career rather than take part-time engineering ourses. There is no single method of ensuring increased entries the engineering industry, and all who are called upon to advise and guide youths should be made aware of the purpose of the industry and the possibilities in it. Headmasters of schools of all types, careers masters, parent-teacher associations and parents are all vital in this matter.

Individual members of staffs of technical colleges and industrial concerns also play an important part through their separate personal contacts. It should be appreciated that many people remember that only 25 years ago first-class engineers, technicians, craftsmen and apprentices were discarded, when trade was bad, by organizations which at present are operating elaborate schemes for the recruitment and training of apprentices of all types. Some of those who were so discarded are now parents of potential apprentices, or are called upon to advise potential apprentices. Only time can remove completely this shadow of the past that is still affecting recruitment to the industry.

DISCUSSION ON

"PROBLEMS OF HYDRO-ELECTRIC DESIGN IN MIXED THERMAL–HYDRO-ELECTRIC SYSTEMS"*

SOUTH-EAST SCOTLAND SUB-CENTRE, AT EDINBURGH, 19TH APRIL, 1955

Mr. C. L. C. Allan: Operating experience over the last few ears has given further proof of the ability of hydro-electric ations to deal satisfactorily with peak-load working. The eed with which plant can be brought on to full load has been seful in dealing with quick demands for extra power, and in the ery cold weather of the past winter the shape of the load curve as such that the highest load had to be sustained only for quite short period of about 15–20 min at times. The co-operation f control staffs has been most valuable in securing the best sults. It was readily appreciated that running the smaller eservoir plants for the very minimum of permissible time in a osty spell of weather with low run-off was of advantage to the upply system and restricted the running of such plants to the ery peaky load periods. Likewise, in October and November, 954, emergency demands for extra power for short periods were et at times when the increase of load was somewhat ahead of e restoration to service of thermal plant after overhaul in outh Scotland and in England.

Operating results show that a larger percentage of hydro-ectric peak-load power can be absorbed on the system than as at one time thought possible or desirable. The reasons r thermal plant not operating to the ideal curve are generally nown and some are mentioned in the paper, Fig. 2 showing the rt of departure from the ideal operating line which takes place. igh-grade plant is not available for long enough, and so more ergy must be produced from poorer plant; it is not possible to ing thermal plants on and off as quickly as would be needed to the upper parts of the curve, and so they generate excess ergy there. These facts seem to indicate that with proper anning and operation there are further advantages to be cured by continuing and increasing peak-load hydro-electric velopment. This is emphasized by the fact that the age and st of production of steam plants at present operating at the p of the duration curve are both very high.

A number of studies of pumped-storage development have been made. These show that with an overall conversion efficiency of about 65% there may not be much gain in the value of the energy produced during the day-time from that absorbed at night. There is, however, considerable gain in the economic production of further energy for use during the heavily loaded periods; moreover, the amount of pumping and day-time running can be selected and planned to fit the operating conditions. The development of nuclear power stations, which, for technical and economic reasons, seem best suited to run at high load factors, is likely to increase the attractions of peak-load hydro-electric power, and such developments are of particular interest in Scotland. There are obvious possible schemes in the Loch Lomond district, which would be near the load-absorbing area. These particular developments would be at a fairly high head, 800 or 900 ft, and it appears that the design of plants capable of pumping under these conditions is worthy of attention now, the more so because similar requirements are no doubt going to arise abroad.

Mr. J. Venters (*communicated*): Section 2.5 introduces two sets of problems—those which must be considered when the plant is in the project stage and those which face the operating engineers once the plant is completed. By the title of the paper it is clear that we are considering a system such as our own, where there is more thermal plant than is needed to maintain the firm hydro-electric output in dry years at a figure at least as high as that for the average year.

In the planning of future hydro-electric projects in Scotland it is legitimate to assume the existence of this thermal plant, and in theory the size of the storage reservoir can be fixed at the point where the incremental cost of additional units obtained by increasing the size of the reservoir balances the fuel cost of the same amount of energy generated in a thermal station. In practice, however, the reasoning provides only a lower limit, and questions of operating flexibility, conservation of fuel, increase in the capacity of the system and the falling value of money, make it clear that over a period of years a much larger storage capacity will eventually prove economic. The civil engineer

* Haldane, T. G. N., and Blackstone, P. L.: *Proceedings I.E.E.*, Paper No. 9 S, November, 1954 (102 A, p. 311).

has thus to use his judgment in deciding how far he dare go in speculating on the future.

The generation engineer of a group of hydro-electric stations must secure the largest monetary return from the rainfall in his catchment. He must therefore produce the maximum amount of firm energy and avoid losing spill energy at overflowing dams. He relies on his storage to gain freedom from short-term weather fluctuations, and hence ample storage contributes to his ease of mind and efficient management of the system.

The authors suggest that the use of thermal plant for firming hydroelectric output is expensive, but this statement needs amplification. I agree when the thermal plant is solely to augment the hydro-electric output in dry years, but in Scotland the overall costs of energy from hydro-electric and thermal plants at the time when they are commissioned are not radically different, and the thermal plant must therefore be credited with its share of the maximum demand. It follows that the cost of firming hydro-electric output is the fuel cost of the extra thermal energy plus the increased cost of operating the thermal station as compared with a hydro-electric station of equal capacity. To give effect to these ideas the hydro-electric stations must be capable of full output at periods of peak load—which is not difficult to arrange, since our peak loads occur in the winter months when rainfall is generally in excess of requirements and the reservoirs are filling up. By comparison, the firming of hydro-electric output is a base-load duty, involving the continuous operation of one or more thermal generating units for weeks at a time at their economic ratings. The amount of such base-load generation can be readily calculated for any year in which there is a shortage of rainfall, and it is remarkable how small it is compared with the total output. Once the peak loads have been met and provision has been made for outages for repairs and maintenance, it is not possible to run the thermal plant in excess of requirements, as such excess operation would merely result in over-filling the reservoirs and so in loss of water.

The hydro-electric generation engineer in Scotland has nothing to guide him but the calendar and his reservoir water levels. He cannot forecast the weather. He must keep his reservoir levels as high as possible (because increased head means more energy recovered per ton of water consumed), but with a few feet of empty storage at the top of each reservoir for trapping storm water when spells of bad weather arrive. It is a question of statistical analysis to determine the optimum water level for each reservoir, the level being higher during the dry months of t year and lower during the wet. If the reservoirs are high, hydr electric generation can be increased and thermal generati reduced until, in the limit, all the thermal stations are shut dow If the reservoirs are below their optimum levels, base-lo thermal generation can be increased until the levels have be restored. So far as I know, no paper has yet been published the statistical determination of the optimum operating levels f reservoirs. Barring permanent changes of climate, a calcu tion once made for a given catchment should serve as an effici guide to the hydro-electric generation engineer for many years.

Messrs. T. G. N. Haldane and **P. L. Blackstone** (*in repl*: We are glad to have Mr. Allan's interesting confirmation the flexibility of hydro-electric plant for the supplying of pe loads and, in particular, to know that operating results ha shown that a larger percentage of hydro-electric peak lo power can be absorbed than was at one time thought possib One of us has a very clear recollection of the difficulties assessing the lowest permissible load factor of the hydro-elect plant at a time when there was little actual operating experien available.

Mr. Allan has drawn attention to the future possibilities pumped storage, and while we agree with his observations, should like to stress the additional advantages obtainable superimposing pumped-storage plant on natural hydro-elect schemes. Pumped-storage plant need not then be debited wi reservoir costs, and any additional tunnel or pipe-line co will be incremental and probably, therefore, comparative low.

In addition to these advantages there are benefits to be obtain from the control of the reservoir levels, a point which is referr to in another connection by Mr. Venters. If pumps are avai able, reservoir levels can be kept higher than would otherwi be possible, with some increase in energy output. Althou this effect may be small for high-head plant, it could beco quite appreciable for low-head plant.

In addition to the advantages already mentioned, the provisi of pumps at a natural hydro-electric scheme may increase t effective storage capacity of a given size of reservoir, and w certainly add a new degree of freedom and flexibility to t operation of the scheme. We agree with Mr. Venters that so statistical work on the determination of the optimum operati level for reservoirs would be desirable.

DISCUSSION ON

"A SHORT MODERN REVIEW OF FUNDAMENTAL ELECTROMAGNETIC THEORY"*

Before the North-Western Centre *at* Manchester *2nd March, and the* Mersey and North Wales Centre *at* Liverpool *29th Novembe* 1954; *also the* North-Eastern Radio and Measurements Group *at* Newcastle upon Tyne *21st March*, 1955.

Mr. L. H. A. Carr (*at Manchester*): In Section 3 the author raises the question of a dimensional constant to represent the concept of shape. Although I know that this is causing some heart-burning in I.E.C. circles, I feel most strongly that neither its discussion nor its use falls within the bounds of science or natural philosophy—that portion of knowledge where expe ment is the criterion and test of credibility—but that it is a matt of concern only to the purely theoretical philosopher.

To the experimental physicist a volume is still a volum whether its unit be taken as a cube of unit side or a sphere unit radius; and to suggest anything different is only to create

* Hammond, P.: Paper No. 1595, December, 1953 (see 101, Part I, p. 147).

ırther and unnecessary difficulty for students to overcome. here is just as much justification for including a further dimensional constant" to indicate whether the ultimate standard kept at Paris or in London.

The paper includes an attempt to reinstate the unit magnetic ole as the foundation of magnetostatics, but the author has ıcceeded in making his argument plausible only by ignoring ıe inconvenient characteristics of this theory.

For any mental concept to be acceptable, it must follow the ame mathematical laws as does the natural phenomenon it presents. The field concept is one of the most useful auxiliary oncepts, and I cannot understand the author's strictures about , unless he considers that it includes some physical aspect that pushes things around." As I, and many others, use it, it is mply a mathematical tool, enabling one to determine more eadily, and evaluate effects due to, "the position and movement f charge," while it is entirely independent of whether those ffects are due to "action at a distance" or not. The field concept ıus only associates a mathematical equation with any particular oint in space, without the postulation of any particular physical ackground.

By the application of field mathematics to the space surroundıg first an isolated electric charge and secondly an isolated ıagnetic pole, the configurations are seen to be entirely disimilar; in the former case there is spherical symmetry; in the atter the only symmetry is axial. Consequently eqns. (1) and (2) re not comparable, and the whole structure of a magnetostatics ased on unit magnetic pole, in the same way that electrostatics an be based on a unit charge, falls to the ground.

In Section 7 the author writes: "By the choice of mass, length nd time as basic dimensional quantities, F has been given the imensions ML/T^2." But following his own line of argument, vith which I entirely agree, there is no *a priori* reason why the wo sides of the equation should be of the same dimensions, ince the experimental data on which it is based refer only to ıe arithmetical figures. If the equation is to be used dimenionally, a dimensional constant must be included, although I gree that it is usual to suppress this and it is frequently very onvenient to do so. It must, however, be realized that such a uppression is a human action, and any difficulties that arise s a consequence are not inherent in nature, but are of our own ıaking.

Similarly, if, following the author, Q is adopted as a fourth asic dimension, the dimensional constant in the equation for orce between charges can be suppressed or not, as we choose, ıe constant κ_0 being a pure numeric in the former case. In ıis case, however, the dimensional constant in the corresponding quation for force in magnetostatics (however expressed) must e retained, as is well known.

This reference to force leads to the question: What do we ıean by force and how do we define it? It seems necessary to tilize this same equation for the purpose, and define force as omething that has the power of bestowing acceleration on a ıass. This, however, brings the concept of motion into the efinition of a force, as does the alternative definition of the pace rate of doing work. It is therefore very doubtful whether orce can be considered without relation to motion or change of ıotion. In this case the simple formula for the force on a onductor carrying current in a stationary magnetic field cannot ıstifiably be applied to a conductor rigidly held in an armature ot, the magnetic field surrounding which undergoes change hile the conductor is in motion.

I have never seen any satisfactory basis put forward for the ypothesis repeated by the author in Section 14 that the mechaical forces in a machine with slotted armature "act largely on ıe iron teeth and not on the conductors in the slot," and I suggest that the author's theories, where he states that "the balance [of energy] can be achieved only by a transformer effect which results in an induced e.m.f. in the coil," if worked out in full detail, would show on the basis of his method of calculation that there was a mechanical force between the conductor and the teeth, resulting in the whole of the force finally coming on the conductor, albeit transmitted to the field-magnet poles through the medium of the armature teeth.

Professor E. Bradshaw (*at Manchester*): "Preoccupation with the doctrine of flux" may by some be thought to be undesirable, but such an attitude does not necessarily follow from the adoption of the M.K.S. rationalized system of units. The author admits that, in support of the concept of the unit magnetic pole, . . . "we impose symmetry"; the symmetries invoked by those who emphasize the field concepts are surely no more artificial. Apart from the welcome, on educational grounds, given to the M.K.S. system by the author, it should be stressed that any teaching sequence can be adopted using this or any other consistent unit system.

In Section 8, in connection with rationalization, the author says that the student "should not be allowed to make his choice until . . ." This is surely a counsel of perfection and assumes a remarkable type of student. Would it not be more realistic to suggest that the student, having first acquired a satisfactory understanding of the basic relations of electrical science via whatever path the teacher deems to be most direct and consistent, may then be exposed to other systems of units and relations?

Mr. E. Wild (*at Manchester*): The fundamental formula assumed in Part 2 for the induced e.m.f. is eqn. (14), e.m.f. $= -$ rate of change of flux. The separation of the rate of change of flux into a transformer part and a motional part [eqn. (22)] is obtained from this by a mathematical transformation. If the two formulae gave different results in any case, there would be a self-contradiction in the theory which would not be removed by the author's device of choosing one formula or the other as correct. It is therefore necessary to reconcile the apparent contradictions.

The fundamental formula applies to continuous motions of linear circuits, i.e. circuits composed of wires of negligible cross-sectional dimensions. If the motion is discontinuous, or if the circuit contains elements of large cross-sectional dimensions, such as the conducting strip in Fig. 8 or the magnet, M, in Fig. 5, through which an infinite number of conducting paths can be drawn, the formula must be supplemented by further conditions, namely

> If the circuit is changed discontinuously, e.g. by switching, the resulting discontinuous change of flux produces no e.m.f.
>
> The law of induction is to be applied only to circuits every part of which moves with the material in which it lies, sliding contacts being permitted.

With these conditions it can be shown that, in all the cases described in Section 15 in which the fields are constant, the flux-cutting and flux-threading rules are equivalent.

The effect of finite cross-sectional dimensions alone is seen in the experiment depicted in Fig. 8. If the circuit through the galvanometer is completed by any line crossing the strip, and moving with the strip, together with the edges of the strip, it can be seen that the flux-threading rule applied to this circuit gives the same results as the flux-cutting rule.

The effect of switching alone is seen in the experiment of winding a coil on to a ring magnet with negligible leakage field by means of a circular slip-ring surrounding the magnet; one end of the coil is attached to the slip-ring at a point A, and the end of the unwound wire has sliding contact with the slip-ring at point C. As the ring rotates, turns are wound on the coil but no e.m.f. is generated. Here there are two circuits to be

considered: those that complete the circuit of the coil through the slip-ring by going from C to A in the sense of rotation and in the opposite sense. The flux through either circuit remains constant as the slip-ring rotates, except when A passes C. Consider the circuit completed by the arc of the slip-ring which goes from C to A in the sense of rotation. The geometrical configuration of the circuit specified in this way changes discontinuously as A passes C, the length of the arc of the slip-ring involved changing from the full circumference to zero. The change cuts out a turn (consisting of the slip-ring itself) wound in the reverse direction, so that the flux increases discontinuously by the amount corresponding to one turn of the coil. Thus the flux through the coil increases discontinuously once per revolution, but the rate of change of flux is always zero, and so is the e.m.f.

The other examples can be explained by a combination of these two methods.

The new derivation of the electromagnetic equations proposed in Part 3 contains a fundamental flaw. Eqn. (41) and eqn. (43), which is derived from it, are self-consistent only if the vector field $\boldsymbol{D}$ satisfies certain conditions, the most general form of which implies that the electric charge has everywhere a definite velocity, the velocity $\boldsymbol{u}$ which occurs in the equations. The equations are thus possible ones for the hydrodynamics of charged fluids in appropriate conditions, but are not adequate for general electromagnetic theory.

The equations, in fact, do not agree with the generally accepted ones, since the current density is not in general, $\boldsymbol{u}$ div $\boldsymbol{D}$. In most engineering applications current flows in electrically neutral media where div $\boldsymbol{D}$ is zero. Eqn. (45) would imply that an uncharged conducting wire carrying a current generates no magnetic field.

Mr. H. B. Daniels (*at Manchester*): The terms "cutting" and "threading" are both used in considering electromagnetism, but I find the idea of "linkage" (of electric and magnetic circuits) very valuable in covering the needs of conduction and radiation of electrical energy. The simplest case to visualize is a circular copper conductor linked with an iron ring, a current in the conductor producing magnetism in the ring, and change of magnetic flux, with which the conductor is linked, producing an e.m.f. in the conductor. This is useful for introductory ideas for material circuits (conduction) and for space (electromagnetic radiation). In the latter case we can imagine the materials removed, and there are still electromagnetic effects in the field of radiation; conduction may be considered as a special case of electromagnetic radiation. Moreover, the wavelength of the electromagnetic propagation is dependent on the frequency of the original electrical oscillation (e.g. in an aerial). The current circuit is based on the physical reality of a quantity of electricity in motion, and thus, with the fourth fundamental quantity accepted as quantity of electricity, we have an M.K.S. system of units unifying conduction and radiation concepts.

Mr. J. E. Macfarlane (*at Liverpool*): If a simple loop is rotated at a uniform speed in a uniform magnetic field and the circuit is complete, a current will flow. This early introduction to electromagnetic theory is best considered as change of flux linkages, the loop being "filled" twice and "emptied" twice in one revolution, i.e. four changes.

Another early demonstration is to plunge a permanent magnet into a solenoid coil connected to a galvanometer. Then, by the principle of work done, the direction of the galvanometer deflection can be both deduced and demonstrated. The demonstration should then be repeated with an electromagnet replacing the permanent magnet, both without and with an iron core. The flux-cutting idea should not be introduced until after these experiments.

M.K.S. units will eventually make things easier for the student. We found last session that a class of civil engineers taking Electrical Engineering Science for the first time accepted the units, and the examination results were satisfactory; but as this is the first session during which M.K.S. units will be in use throughout Liverpool technical colleges, a few years' experience will be needed to show the overall effect.

Mr. D. Chalmers (*at Liverpool*): Until the introduction of M.K.S. units my starting point when teaching electromagnetic theory was to use the expression for the force between two magnetic poles, $F = m_1 m_2 / \mu d^2$ dynes, in C.G.S. units. From this expression μ can be more or less determined and a whole system of magnetic and electrical units constructed.

Since the suggested use of the M.K.S. system I have modified the teaching sequence; for example, it is possible to show parallel concepts in the conduction, magnetic and electrostatic circuits as follow:

Conduction circuit.—Current density = conductivity × voltage gradient.
Magnetic circuit.—Magnetic flux density = permeability × magnetizing force.
Electric flux density.—Permittivity × electric field intensity.

The three circuits have three analogous quantities: (*a*) current density, magnetic flux density and electric flux density, which can be regarded as the effect; (*b*) conductivity, permeability and permittivity, regarded as the associated material constants; (*c*) voltage gradient, magnetizing force and electric field intensity, regarded as the cause. Admitting that there are in the magnetic and electrostatic cases two unknown quantities, permeability and permittivity, a rational system of units can then be established using the M.K.S. system.

From my teaching experience the M.K.S. system has been favourably accepted by students, although in first- and second-year students in technical colleges the appreciation of the absolute permeability of $\mu_0 = 4\pi \times 10^{-7}$ Wb/m² per AT/m is somewhat vague.

Mr. E. D. Taylor (*at Newcastle upon Tyne*): There will be little opposition to the proposal that the electrical engineering student should be given a logical presentation of the fundamentals of electromagnetism; indeed, if he is worth his salt he should demand it for himself and will choose the presentation that seems the most satisfactory. Another person to whom the presentation is important is the man in industry who has to solve individual electromagnetic problems, perhaps for design purposes or for explaining phenomena. His needs are not merely a logical presentation, but practice in applying and thinking around the basic equations, not in the sense of mathematical analysis, but in the sense of understanding what are assumptions, what are deductions, what are experimental data and what are merely convenient ways of looking at things, such as, for example, Fig. 1 and its explanation. I suggest that more could be done in setting students some of the problems that are illustrated in Figs. 4, 5, 6 and 9. Besides these, there are other simpler and more common ones in shielding, short-circuited turns and so on which require considerable clarity of thought.

It is questionable whether the paper really displays a completely logical sequence of clear thought; for example, in the ready acceptance of the vectors $\boldsymbol{B}$ and $\boldsymbol{D}$ in eqns. (9) and (10) and rejection of vector $\boldsymbol{A}$ in eqn. (15), particularly since vector potential is such a powerful tool in later work besides helping to avoid much of the confusion met with by the statement of Neumann's law. Similarly, a mind which appreciates the symmetry of equations will surely ask the question that leads to $\boldsymbol{A}$, namely: "$\boldsymbol{B}$ being a vector, of what could it be the derivative?" Again, current elements are not favoured as being

ınrealizable, although there is ready acceptance of Fig. 1(*b*), vhich is equally unrealizable.

With respect to the symmetry of the equations, mathematical ymmetry is, after all, a subtle point. It certainly has to be orced on the equations with the need for magnetic conduction-urrent density (= 0). Asymmetry itself is valuable in drawing ttention. Here it makes us pay attention to the first and implest electromagnetic observation, namely that the magnetic ield, unlike the electric field, has zero divergence, i.e. when the nagnetic field is due to currents, there are no sources of magnetic lux which correspond to electric charges as sources of electric lux. In any case, the equations are really no easier to remember, nd the need for displacement current, if not all the reasoning eading up to it, is clear by trying to omit it from eqn. (38); liv. ***i*** is then zero, which is absurd.

Mr. G. H. Hickling (*at Newcastle upon Tyne*): The Faraday-lisc experiment, and the variations on this of the rotating nagnet generator and the homopolar motor, serve to illustrate ircumstances in which only the flux-cutting rule for the genera-ion of e.m.f. (and the inverse effect in the last example) is pplicable. The more important deduction to be drawn from hese experimental demonstrations, however, concerns the nanner in which the electric circuit and the magnetic field must e defined in applying these rules. In each of these instances the eometrical form and position of the electric circuit is kept ixed, as is the path in which the current flows; but in each instance part of the metallic conductor comprising the circuit is in notion in the field, carrying with it the charges on which the lectromagnetic forces consequently act. A further familiar xample of this is the eddy-current disc in the induction watt-hour neter.

Equally significant is the deduction that the magnetic field lue to the bar magnet rotating about its axis remains at rest, ven inside the magnet itself. The view to be taken here, evi-lently, is that the field is a mass effect due to many molecular nagnets (or electron spins) and remains unaffected so long as he distribution of these in the region considered is not dis-urbed.

Concerning the general thesis of the paper, I would fully oncur with the author's wish to develop the electrostatic and lectromagnetic series of units in symmetrical form from the nverse-square law of forces on the unit charge and unit pole, he two systems being linked ultimately by the connecting onstant of 3×10^{10} cm/sec. It is unfortunate, however, that his is linked in the paper with the application of vector notation, vhich, however useful, is unfamiliar to the elementary student. urthermore, I believe that the development of the unit systems very much clarified by defining the unit of force as 1 dyne in qns. (1) and (2), rendering the constants α and β unnecessary.

Mr. W. E. Burnand (*communicated*): I question whether linkage, utting or detached magnetic poles form the complete story of lectromagnetic induction; I think that there is also another omponent.

Consider Fig. D. P is a copper tube and S_1 is a conductor ıside P. S_2 is a conductor outside P but inside a substantial minated iron cylinder Fe. It is well known that no magnetic eld is generated inside a tube carrying a uniformly distributed ırrent longitudinally.

If now a current is passed along P, a magnetic field is generated ound it (but not inside), proportional to the current in the tube nd the magnetic permeability of its surroundings, and inversely roportional to the radial distance. With an alternating current long P of such a value that Fe is not saturated, the field in the r spaces is small and may be neglected for the purpose of the resent discussion, the significant field being that in the laminated on cylinder. The voltage induced in P, S_1 and S_2 by the varying

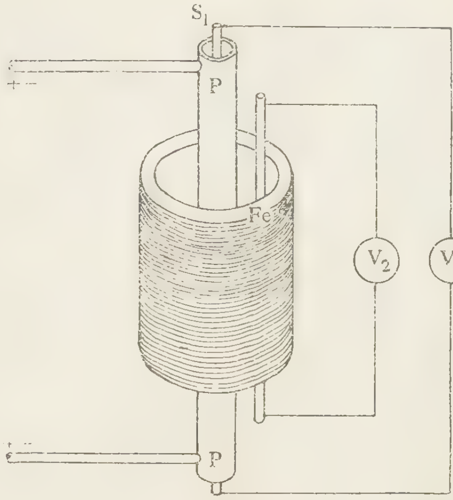

Fig. D

magnetic field of Fe is the same. In the space between P and Fe there is the m.m.f. spreading out from P and the small magnetic flux, but inside P there is neither m.m.f. nor magnetic flux; but there is still the same voltage induced in S_1. As the radiation from P is all outwards, it follows that the induced voltages are due, not to this outward radiation, but to an inward radiation from the varying magnetic field, which, moreover, is of a different character to the outward radiation, since it has neither m.m.f. nor magnetic flux.

Normally the whole of the induced voltage can be considered as confined to the space surrounded by Fe, and in fact is so, as evidenced by the performance of innumerable current transformers in daily use. But the possibility arises that there might be some way in which this non-magnetic voltage-inducing component could be projected beyond the plane of the generating field, analogous to the way in which the electromagnetic wave is projected in the usual radio transmission.

If the magnetic field round a series of copper conductors is explored as these are progressively added till they form an elongated cage, it will be found that as these reach a circle they form the equivalent of a tube, in that the magnetic field goes completely outside the circle leaving the inside clear of magnetic flux; but the full inductive effect remains.

A large circle of vertical conductors, fairly close together but of the dimensions of a Druid circle, caused to oscillate in unison under crystal control, looks an attractive experiment, since this would radiate the usual electromagnetic wave outwards from the circle and the different, voltage-inducing non-magnetic component from the inside. Since this latter component is created in any case by a more or less circular varying magnetic field, it seemed worth trying a fairly large toroidal coil, in spite of the fact that the non-radiating property of the toroid is so universally recognized and made use of in radio apparatus.

A toroid of about 30 in diameter was therefore constructed, using a piece of rubber hose bent into a circle and wound uniformly with about 2 000 turns of 22-gauge copper wire. When a small current (about 0·4 amp) was passed at about 2 kc/s by means of a valve of unknown characteristics, the characteristic squeal was readily picked up at a distance of 7 ft by means of a search coil and amplifier, the coil being about 7 in in diameter and having 64 turns, the assembly being as indicated in Fig. E.

Another search coil of nearly the same diameter as the toroid gave similar results. The loudest signal was received with the toroid transmitter and straight-coil receiver squarely facing.

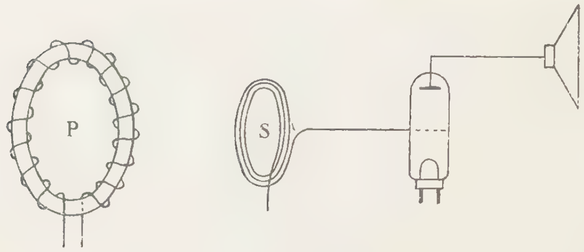

Fig. E

With the toroid turned through 90° so as to face the receiving coil edgewise, or the search coil turned 90° facing the transmitter edgewise, the signals ceased.

Thus we have transmission through space with no magnetic interlinkage, no magnetic flux or m.m.f. projected from the toroid, no "cutting" or varying "linkage" of magnetic flux, and the conductors in the transmitting toroid at right angles to those in the receiver or secondary circuit.

Static can be ruled out, as signals ceased when the toroid winding was opened at its mid-point. Transmission was effective throughout the audible range of frequency and also when the toroid was fed from a 500c/s alternator about 40ft away as a check on whether signals were picked up from the valve oscillator. There is still left the third component or element as the transmitting agent.

Dr. R. Feinberg also contributed to the discussion at Manchester and **Mr. A. O. Carter** at Newcastle upon Tyne.

Mr. P. Hammond (*in reply*): Mr. Carr objects to the use of the concept of pole strength, because the field around an electric charge exhibits spherical symmetry, but around an isolated pole there is axial symmetry. If this were indeed so, I should be the first to abandon the concept of pole strength. But Mr. Carr's statement is equivalent to saying that the law of force between poles is not that of the inverse square. Because the laws *are* identical for electric charges and magnetic poles, their field patterns are identical. In fact, the field around an isolated charge and the field around an isolated pole both exhibit spherical symmetry. This is the justification for the invention of the twin concepts of a point charge and a point pole. It would hardly be an exaggeration to say that this approach halves the mental effort required from the student. I agree with Professor Bradshaw that the M.K.S. system need not be tied to a particular sequence of instruction. It is all the more regrettable that the over-enthusiastic supporters of the system wish to give it a philosophical content that it does not possess by tying it to the Maxwellian aether theories. The subsidiary conditions that Mr. Wild attaches to Faraday's law will undoubtedly give the correct answer, but to some students the conditions may appear unconvincing. For instance, how can the rate of change of flux be always zero and yet the flux be increasing? If the flux increases discontinuously, will not its rate of change be infinite? Surely all these conditions are unnecessary, if it is realized that eqn. (18) is identical with eqn. (22). I would urge Mr. Wild to re-read Section 16 of the paper. With regard to eqns. (4 and (43), div $\boldsymbol{D}$ is not zero in a conductor. Every electr implies that there is a divergence of $\boldsymbol{D}$.

I find Mr. Burnand's contribution very difficult to understand. The success of Maxwell's theory has been such that it seems unlikely that a completely new type of radiation would have to be postulated to account for Mr. Burnand's experimental evidence. The trouble experienced by Mr. Burnand seems to arise from a too ready acceptance of such statements as that contained in his second paragraph. There is, in fact, always a magnetic field inside a tubular conductor carrying alternating current, in spite of the widespread belief to the contrary. Similarly, there is a magnetic field outside a solenoid. Lack of space prevents a detailed analysis here, and I would refer Mr. Burnand to Professor E. B. Moullin's book "Radio Aerials" where these problems and many similar ones are treated in detail.

Although the paper dealt only in passing with the M.K.S. system of units, much of the discussion has centred on the issues arising from the introduction of this system into electrical engineering courses. It seems that to many speakers the alteration in the size of the basic units implies also a change in the sequence of instruction that is to be used. Because the units are relatively new, and hence progressive, we are urged to embrace also the new and progressive sequence of instruction. I still hold the opinion expressed in Part 1 of the paper. A mere shifting about of factors such as 4π or 10^8 can never contribute to a clearer understanding of electrical science. To believe with Mr. Macfarlane that students gain an understanding of electrical matters more easily in M.K.S. units is almost equivalent to a belief that we should all be richer if we had a decimal system of currency. Mr. Chalmers rightly points out what is in store for us teachers when he says, in a masterly understatement, that the appreciation of certain students of the nature of absolute permeability is somewhat vague. There is no doubt that the vagueness arises largely from a return in teaching to the view of Gilbert (*c.* A.D. 1600), who thought of electricity in terms of orbs of virtue surrounding electrified bodies.

I find myself in almost complete agreement with Mr. Taylor. The vector potential is far too useful a tool to be dismissed lightly. It might well be argued that the delayed potentials are more useful to the electrical engineer than Maxwell's equations, because the potentials already include the boundary conditions of the problem. Nevertheless, it seems to me that a clearer picture of electromagnetic radiation is conveyed by a sequence of instruction that starts with electric and magnetic charges, goes on to the forces exerted by these charges and only then introduces the idea of potential as a convenient device used in the summation of forces. I am grateful to Mr. Hickling for his clear statement of the flux-cutting effect and of the action of a rotating magnet. Vector algebra is certainly not necessary for the presentation of the matter contained in the paper. We use it only with students reading for Part II of the Mechanical Sciences Tripos.

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Paper No. 1939 U
Oct. 1955

A HIGH-POWER MECHANICAL CONTACT RECTIFIER

By J. C. READ, D.Sc., Member, and C. F. GIMSON.

(*The paper was first received* 22nd *June, and in revised form* 16*th August*, 1955.)

SUMMARY

The paper deals with a recent design of mechanical contact rectifier, ed at 15 kA and 220–270 volts, which has been developed in this intry. Its constructional features and the reasons for adopting the angements selected are described in detail, and a brief account is ren of the results obtained. The overall efficiency is over 97%.

(1) INTRODUCTION

During the past five years the development has been completed a new design of high-power mechanical contact rectifier, and e paper describes its features and operating results. The paper als particularly with those points where there are differences om established practice.

The first successful high-power contact rectifiers were conucted in Germany just before and during the war, mainly rough the work of Koppelmann and his associates.[1,2] Under e difficult war-time conditions the performance of these ctifiers was somewhat mixed,[3] but they showed that a practical vice on such lines was in sight, whose high efficiency would ove a marked advantage for low-voltage heavy-current electrotic duty. The many new problems still to be worked out with is type of plant, coupled with the urgent difficulties of reganization that faced the British manufacturing industry in the st years after the war, delayed any attempt to build such rectifiers in this country. However, in 1950 the development was undertaken of a contact rectifier for electrolytic service. After study it was agreed that a rating of 15 kA at 220–270 volts represented the most generally convenient and economical size of unit, and a full-size prototype equipment was accordingly put in hand.

The team of engineers engaged on the project endeavoured to study all aspects of the problem *de novo*, and to work out their own solutions. Despite many untried features, once the components of the prototype set were completed and assembled the tests proceeded with unexpected celerity. After works trial of certain alternative constructions the prototype was installed in 1954 for service experience (Fig. 1), and ten more sets of similar rating were put in hand.

The prototype had been made bulky in some respects, so as to afford the liberal design margins, easy access and facility for making changes that are desirable in experimental plant. In the later sets this was no longer necessary, and a neater and more compact arrangement could be made; however, the essentials remained unchanged.

(2) ELEMENTARY PRINCIPLES OF CONTACT RECTIFIERS IN GENERAL

The features that are general to all rectifiers operating on this principle have been so well and frequently described[4–10] that only the briefest recapitulation is necessary here, mainly to define the terms used.

The principal circuit components and the resulting method of

Vritten contributions on papers published without being read at meetings are ited for consideration with a view to publication.
Dr. Read and Mr. Gimson are with the British Thomson-Houston Co., Ltd.

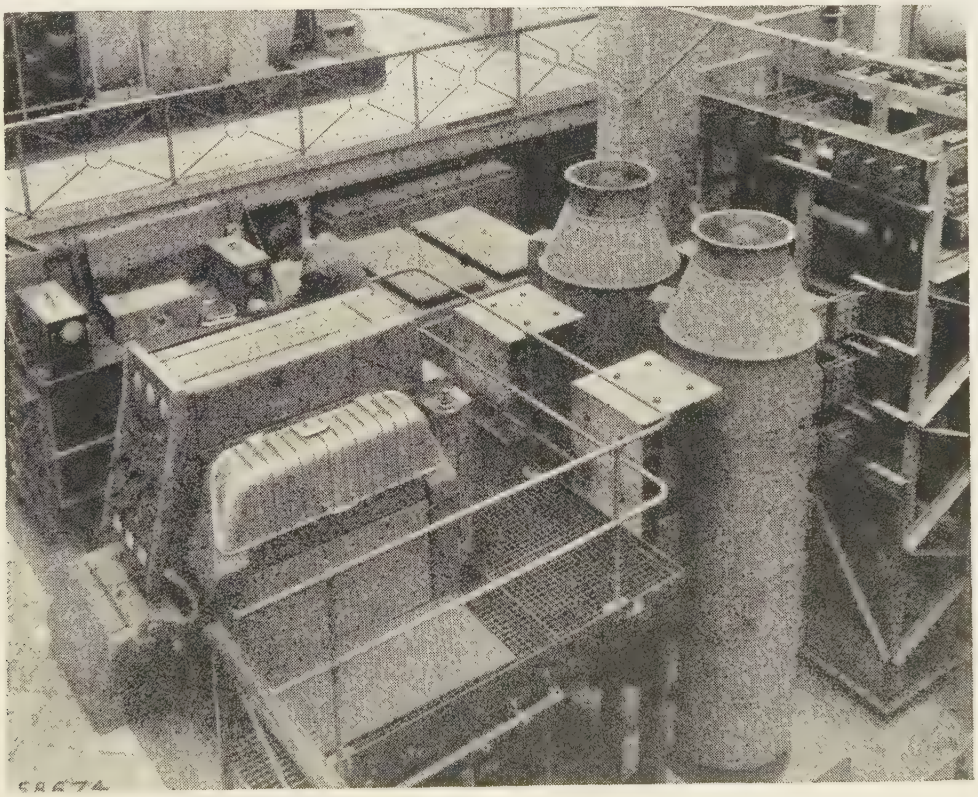


Fig. 1.—Prototype in service in a chemical works.

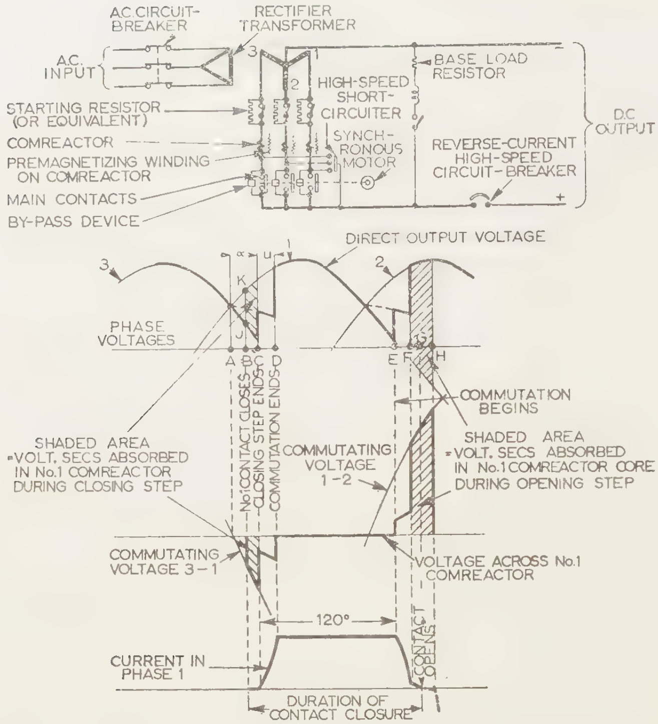


Fig. 2.—Elementary connections and operation of a simplified contact rectifier.

The shaded areas equal the volt-seconds absorbed in No. 1 comreactor during the opening and closing steps respectively.

operation are summarized in Fig. 2. Rectification is effected by the synchronous closing and opening of small mechanically-operated contacts, with the aid of premagnetized commutating reactors (for brevity called "comreactors") of special construction, which form a low-current step in the wave, and of by-pass devices in parallel with the contacts. A series starting resistor (or other means) and a temporary base-load resistor are necessary. In the event of flashover at the synchronous contacts ("backfire"), a special high-speed short-circuiting device operates to minimize damage. The output voltage can be controlled by phase retardation through an angle α, produced by mechanical and/or electrical means. The mechanical unit has to maintain the instants of contact closing and opening correct, and in particular to ensure that the contacts open during the opening step; the premagnetized comreactors and the by-pass circuits serve mainly to reduce the current and voltage broken by the opening contact to something below about 0·5 amp or 10 volts.[11]

(3) DESIGN FEATURES ADOPTED

(3.1) Choice of Main Circuit Arrangements

The various possible alternatives had to be worked out in much detail, since the relationships between the different components interlock much more than would appear at first sight. The account which follows, of some of the schemes considered and the reasons for choosing or discarding them, is thus rather oversimplified.

To provide the voltage range required it was decided to provide on-load tap-changing on the transformer, the use of phase control being restricted to short periods of time or fine adjustment. This arrangement gives the best power factor and waveforms, and also the most effective use of the flattening circuits (Section 3.4.4) and thus good prospect of long contact life.

In the authors' opinion it is always desirable to keep the number of contacts to the minimum, so as to avoid unnecessa mechanical complication, first cost and maintenance cost. Th dictated that the number of contacts in the mechanical un should be 12, since this number is sufficient to enable an a cooled contact construction to give the desired rating of 15 k and is also the minimum with which 12-phase waveforms ca be obtained.

For transformer connections the 6-phase polygon arrangeme (Fig. 3) appeared at first sight very attractive, for its low co

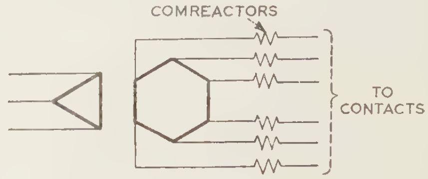


Fig. 3.—Polygon connection.

mutating voltage means that for a given cost of comreactors t step length can be made longer than with other connectio (although this is largely offset by the fact that for a given pe centage reactance the angle of overlap is larger, so that there more necessity for a lengthy step). For this application th polygon connection was not adopted, for the following reason

(*a*) The increased contact heating would have necessitated reduci the output current from 15 to about 10 kA, with higher cost p kilowatt.

(*b*) With 12 contacts the polygon connection gives only 6-pha waveforms, whereas 12-phase operation was desired.

(*c*) Since the contact has to remain open for a longer porti of the cycle, difficulty arises in keeping the stress in the contact spri within safe limits. This difficulty can be overcome in various wa but these all result in increased complication, and they appeared the authors likely to make contact maintenance more difficult.

The most attractive choice then lay between the single-wa and double-way transformer connections on the lines shown Fig. 4 (for simplicity drawn for only six contacts). With t

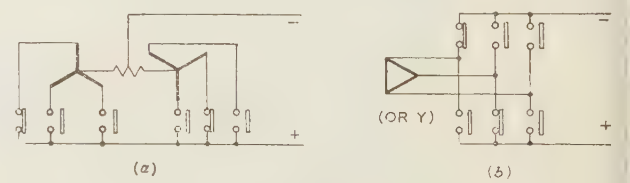


Fig. 4.—Typical alternative transformer connections (comreactors not shown).

(*a*) Single-way. (*b*) Double-way (bridge).

single-way connection the voltage handled by the contac although doubled, would still have been practicable, and the would have been a valuable saving in the copper from the tran former to the comreactors and onwards to the mechanical uni On the other hand, a 41% increase in the size of the tran former secondary winding would have been required, wi increased loss and complication in these heavy-current winding and (since a 12-phase quadruple-zigzag secondary windin would not have been feasible) it would have been impossible obtain 12 phases economically, particularly in conjunction wi the use of tap-change equipment. The double-way connectio was therefore adopted.

The prototype was built for 6-phase operation, to gi flexibility to enable alternative connections to be tested; it th comprised essentially two identical 7·5 kA 6-contact circuits parallel. For the subsequent ten sets, however, because of t large total power, it was specified that each set should gi 12-phase operation. It was found practicable to construct t

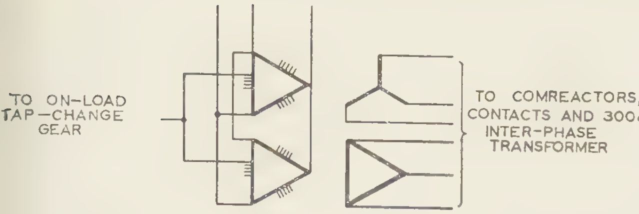


Fig. 5.—12-phase transformer connection as used.

2-phase transformer as shown in Fig. 5, thus making the effect f the tap-change gear identical for the two halves of the set and imiting certain undesired interactions between the two halves o a permissible level. There are respectively four and seven urns per phase in the secondary windings, giving a turns ratio iear enough to 1 : 1·732 to be compensated for in the pre- iagnetization of the comreactors.

The earlier German and American contact rectifiers had em- ıloyed double-way connection of the comreactors, as shown in

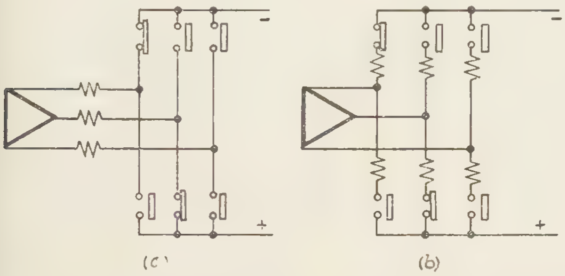


Fig. 6.—Alternative connections of comreactors.
(*a*) Double-way. (*b*) Single-way.

ig. 6(*a*). It had long been recognized that with this connection nly 60 electrical degrees are available for the total of commuta- ion, opening step, margin and closing step, and therefore that the otal reactance of the circuit had to be made inconveniently low nd the step lengths rather short; but it had been believed that cceptance of these disadvantages was justified by economy. Iowever, on examination, the supposed economic advantage of ıe double-way comreactor connection proved to be illusory or the following reasons:

(*a*) The very low reactance needed with the double-way connection demands that the comreactor is wound with a small number of turns. For a given step length this requires a proportionately larger weight of the costly special core material.

(*b*) The double-way connection requires a small separate core for the closing step, whereas the single-way connection [Fig. 6(*b*)] uses the same core for both purposes. The extra core for the closing step is costly out of proportion to its size, owing to the exceptionally thin core material that has to be used in it by reason of its very short flux-reversal time.

(*c*) The double-way connection, on account of its relatively short step length and therefore rapid flux reversal, requires thinner material than the single-way connection in its main core also, again involving higher cost per pound of core material.

On the other hand, the single-way comreactor requires a more ostly and elaborate premagnetizing circuit.

The result of this comparison showed that no economic andicap would be incurred by adopting the single-way com- actors, which, however, conferred the following further dvantages:

(*d*) Higher permissible reactance; consequently lower fault currents, more economical transformer design, and practical freedom from operation being affected by the value of the reactance in the supply system.

(*e*) Longer permissible opening step; consequently more margin for contact timing errors.

(*f*) Smaller step current, owing to the larger number of turns on the comreactor; consequently less current to be broken by the synchronous contact.

(*g*) Plenty of time for the closing step; consequently phase control can be effected entirely by varying the length of closing step, instead of by mechanically varying the instant at which the contacts close.

For these reasons, the single-way connection of the com- reactors was adopted [Fig. 6(*b*)]. The main connections of the sets as a whole are thus as shown in Fig. 7.

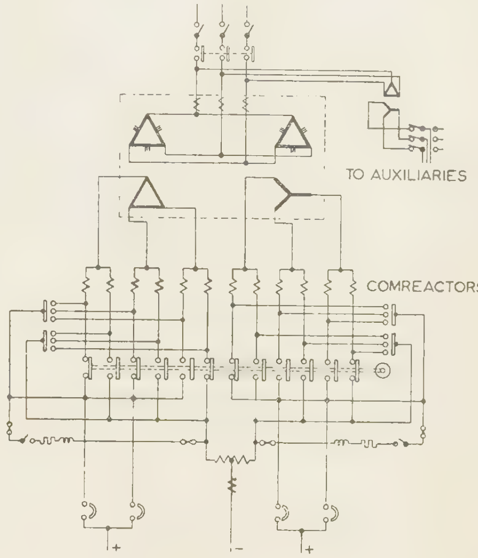


Fig. 7.—Main connections of 15 kA 220–270 volt 12-phase contact rectifier.
Premagnetization and by-pass circuits, and tripping circuit for short-circuiters, are not shown.

In the early designs of contact rectifiers a considerable part of the contact wear was produced by sparking at closing, mainly due to bouncing, and so long as the contact closed with con- siderable voltage across it this still remained a problem even with the most refined arrangements for producing a closing step. The adoption of single-way comreactors, with phase-control produced entirely by the length of the closing step, made it possible to effect a more radical reduction of sparking at closure, by arranging for the contact to close under all circumstances with practically zero voltage across it.

This, however, requires that the position of closing shall remain constant, whereas the position of contact opening must vary as the position of the opening step varies in the cycle with load and other conditions. If the variation of contact timing is made by the usual method of changing the effective length of the push-rod, the instants of opening and closing are shifted by equal and opposite amounts; while if the variation is made by moving the synchronous driving motor, the instants of opening and closing are shifted by equal amounts in the same direction. There is thus no single, simple method of shifting the instant of opening without also shifting the instant of closing. It has therefore been usual either to use a single contact per phase and tolerate closing with voltage across the contact, or to use two contacts in series, one to close the circuit and one to open it.

It was desired to combine, if possible, the good features of both these schemes. In the arrangement adopted the common overlap control shaft in the mechanical unit, which varies the effective length of all the push-rods together, is connected by a cam to a mechanism which turns the stator of the synchronous driving motor. The two effects—change of push-rods length and shift of driving motor—are thus made additive as regards the instant of contact opening, while they approximately cancel one another out as regards the instant of contact closing.

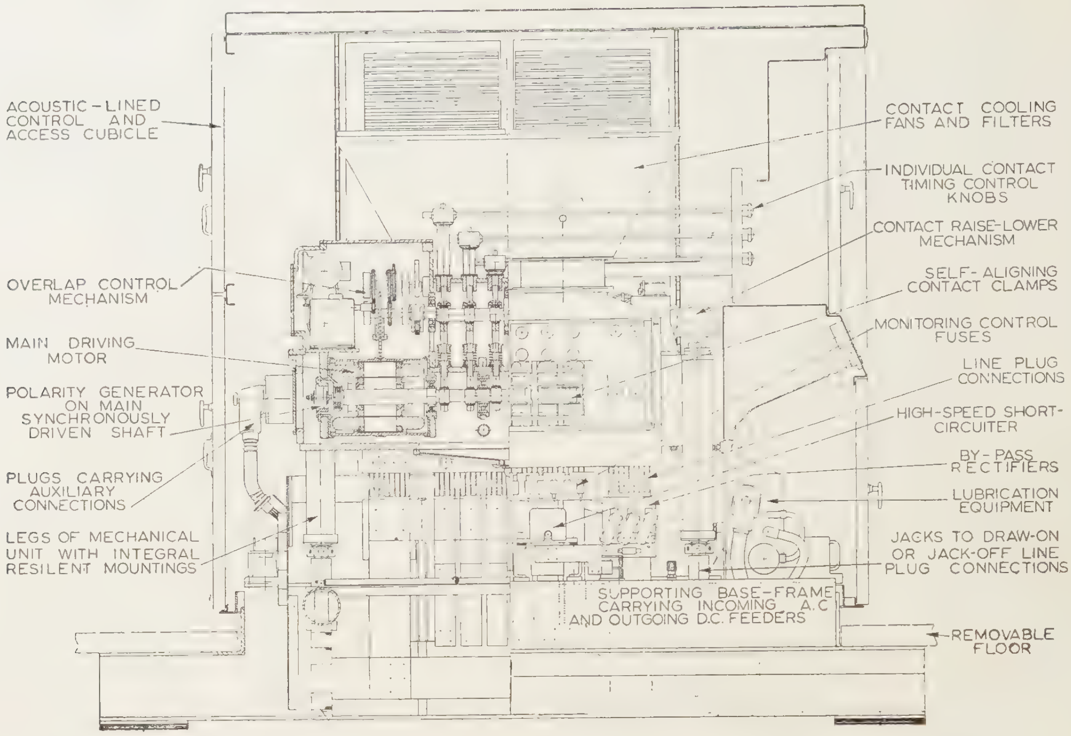


Fig. 8.—General arrangement of mechanical unit.

(3.2) Mechanical Unit

(3.2.1) General Considerations.

The mechanical unit followed in general the well-defined principles that had been laid down in the earlier designs by the German manufacturers. However, it was felt that this was such an important application that considerable attention should be given to the accessibility and maintenance, and as such the mechanical unit has been made so that it may be removed without too much dismantling from the main equipment, taken away for servicing and inspection, and replaced with the minimum of inconvenience.

This led to a design in which the mechanical unit is situated on the top of the comreactor assembly and connected through plugs and sockets. This was further shown to be an advantage in view of the site layout at the chemical works. In this case the heavy-current connections, both a.c. and d.c., could be fed up through the floor, leaving the mechanical unit on the top-floor level.

To facilitate a straight run of copper connections for the plugs and sockets the design was arranged so that the synchronous driving unit is in the centre of the contact structure, two sets of connections with their six contacts being mounted down each side.

This also made it easier to meet the requirements regarding ventilation and lining-up in general with other equipment at the same substation, where the down-draught scheme is used. This is done by means of four fans, two on the top of each side contact chamber, drawing air through filters and discharging into the basement. This construction also favoured the mounting of the whole equipment in a soundproof enclosing cubicle, designed so that only the minimum of operating gear is brought outside, as shown in Fig. 8.

(3.2.2) Mechanical Features.

A study of the earlier designs of rectifier indicated that they had a mechanism including a multiplicity of pin-type bearings, resulting in slight deviations from the ideal of sine-wave motio The mechanical unit under discussion has been designed to avoi where possible, pin-type bearings, replacing these with flexib steel spring mountings. The resulting sine-wave motion als results in less wear on the needle roller bearings on the ma shaft. Deviations from the sine wave result in uneven speeds o the rollers, bringing about slipping and consequent wear. Th design of the supporting springs is obviously a study in itsel and it is of paramount importance that surging be eliminate since this would materially reduce the life of the components.

Fig. 9 shows a cross-section of one phase. It will be note that all six phases are identical except for the displacement o the eccentrics on the main shaft.

The method of opening and closing of the contacts is conven tional in form, the push-rods themselves being of hollow ste construction fitted with insulating push-rod ends. The nece sary adjustment of the push-rod length in order to achieve corre timing conditions takes two forms. The first is an overall adjus ment of the timing of all contacts simultaneously, as dictated b load conditions; this takes the form of wedges interposed betwee the central operating block and the ends of the push-rods, whic are moved up and down as controlled by the angular displac ment of the overlap control shaft. The second form of adjus ment is necessary to take care of individual variations in the con tacts themselves. This is achieved by complementary wedges, als spring-mounted, which, through a parallel-motion mechanism may be adjusted by hand from the front of the cubicle whi the unit is running.

The busbar structure is noteworthy, as it is necessary here t provide great mechanical rigidity to maintain the very clos accuracy of contact timing required and at the same time moun and insulate large connections without having to resort to high degree of cooling.

The driving motor was designed to be of the unexcited syn chronous type, since this is able to follow more closely transien

variations in frequency, and it results in a very robust mechanical construction of much smaller dimensions, eliminating slip-rings and brushes. It can be shown that the load-angle variation is about half that of the fully-excited synchronous type.

(3.2.3) **Lubrication.**

The lubrication required by the mechanical unit is such that it was decided to make a separate entity of the pump-driving motor and oil sump. This has the advantage that, while the mechanical unit itself tends to be heated by eddy-current losses in the steel, this heating does not have the effect of raising the lubricating oil to a dangerous temperature.

The lubricating circuit comprises a main filtered oil pressure-feed which flows through a reducing valve, making oil available to the mechanical unit at two pressures. The high-pressure feed is led through to the push-rods and to the overlap-control wedge mechanism, while the low-pressure section is fed into the main shaft to lubricate the ball and roller bearings incorporated in this structure.

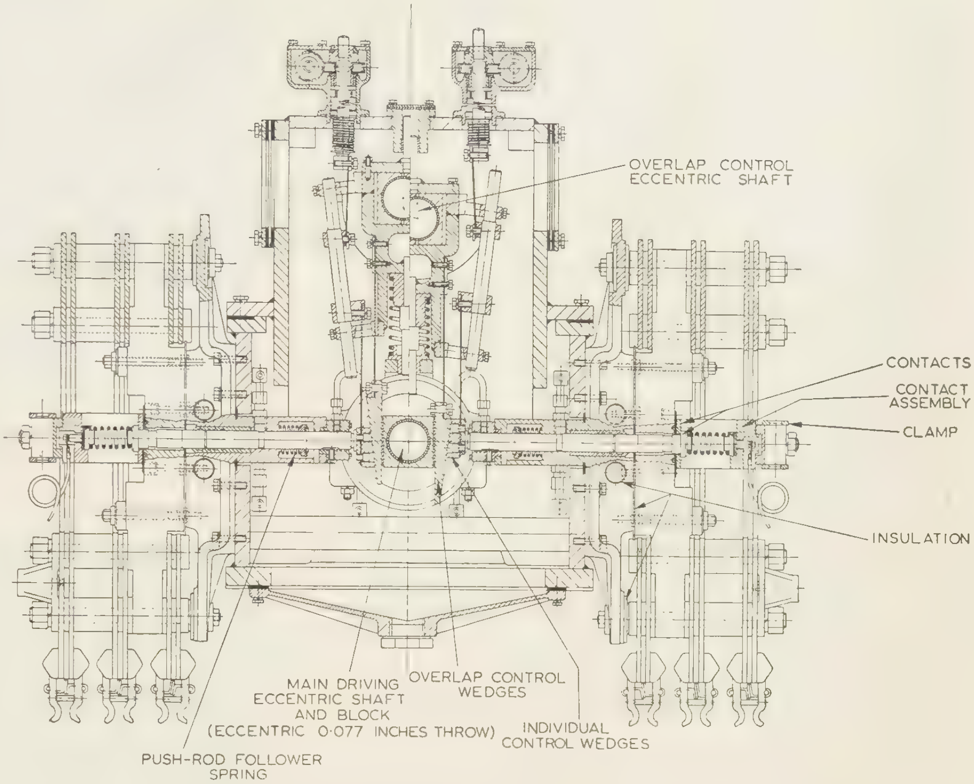


Fig. 9.—Sectional view of one phase-assembly with its relationship to actuating contacts.

The lubrication of the remainder of the equipment is achieved by splashing from the rotating shaft, and this appears to be perfectly satisfactory. However, the presence of much oil and oil vapour within the structure results in some small leakage along the push-rods, which, unless dealt with, finds its way to the main contacts, causing heating. This has been avoided by a vacuum pump, driven from the shaft of the main lubrication oil pump, creating a pressure drop at the outer end of the bearing bushes of the push-rods.

A series of pressure and vacuum switches have been provided to operate an alarm system should the operating conditions deviate too much from the normal. The alarm system gives warning and is backed by a secondary system which will result in emergency tripping of the oil switch if unsatisfactory lubrication conditions prevail long enough to risk serious mechanical damage.

It is necessary to ensure that the oil is maintained at a constant temperature, in order that the load angle of the driving motor does not vary unduly. This is achieved by preheating the oil by a thermostat-controlled immersion heater in the oil tank. In actual running the oil heater is required only when the unit is being started up or is running on light load, and the thermostat is set below normal running temperature, the eddy-current losses in the main mechanical unit providing sufficient heat to maintain the temperature after the unit has been running for a short period.

(3.2.4) **Contacts.**

The contact assembly comprises a moulded carrier supporting two fixed contacts on its bottom end, the moving contact being loaded and held in position by the contact spring in the conventional manner. The position of the moving contact is defined accurately by a contact-guiding diaphragm of glass-impregnated insulating material. It is necessary that the whole of this structure is made and located with extreme accuracy, since the moving contact must make and break contact with both fixed contacts simultaneously within close limits.

The contact life under normal conditions is many thousands of hours, although it may be necessary to undertake resurfacing of the contacts when pip-and-crater formation becomes too accentuated. This servicing must therefore be done with great care, in order to maintain the original standard of accuracy.

Earlier designs of contact were made of copper with silver facings, but owing to difficulties in ensuring 100% adhesion between the silver and the copper it has now been decided to abandon the bimetal construction in favour of solid silver for both fixed and moving contacts. The contacts themselves are located concentric with the push-rods and bolted on the busbar construction in pairs, a single bolt securing them on their dowels. It is thus possible to replace all contacts very quickly.

In the early stages of the development work numerous designs of contact spring were tried in an attempt to avoid surging. Surging in itself resulted in reducing the life of the springs, at the same time giving rise to overheating, contact bounce and metallic flaking of contact surfaces. The actual development took a full circle from normal helical springs, through conical helical springs, springs of butterfly design, and finally back to a much superior and more carefully designed form of conventional helical spring. The manufacture of these springs requires very careful control, for quite trivial abnormalities such as grinding marks lead to relatively early failures.

(3.3) Commutating Reactors

The requirements in the comreactors are a high saturation flux with minimum air flux, low coercivity and the sharpest possible change from the saturated to the unsaturated condition.

This necessitates using ring cores of a special magnetic material, with a toroidal winding surrounding the core section as closely as possible.

The special core material, H.C.R. alloy, is an almost pure 50% nickel-iron alloy, in which a high degree of preferred grain orientation is produced by a process of severe cold rolling followed by an anneal in pure hydrogen at a critically determined temperature.[12] The core is made up of sections, each consisting of a spiral of thin H.C.R.-alloy tape 1 in wide and weighing about 50 lb, insulated with refractory oxide. The manufacture of these core sections was undertaken by the makers of the alloy, and the problems of obtaining sufficiently good magnetic characteristics in such large core sections proved considerable. However, the makers steadily improved their technique, increasing the rectangularity of the curve and reducing the coercivity, and finally achieved excellent results. A typical B/H characteristic for a full-sized core section is shown in Fig. 10.

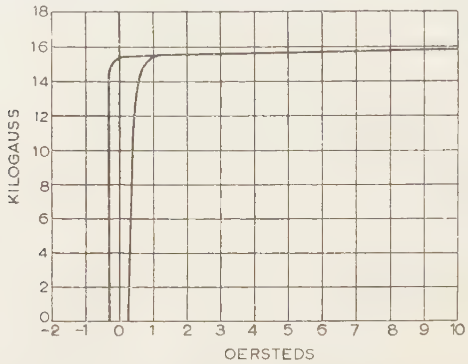


Fig. 10.—Typical dynamic B/H loop for full-size core section.
Flux reversal time = 1·5 millisec.

For these critical requirements the classical ballistic-galvanometer methods of plotting the B/H loop, which correspond to slow flux reversal, are quite unsuitable, since as the speed of flux reversal is increased the eddy currents cause the loop to become broader and its corners more rounded. A new apparatus for accurately determining the complete B/H loop at the actual flux-reversal speed, based on the use of a high-speed Carpenter relay, was devised by Mr. D. Edmundson and used for testing all core sections and completed cores.

The shape of the B/H loop with this material can easily be spoiled by mechanical strain. The reactors are therefore designed with axis vertical, since in this way strains can be kept to the minimum. Each complete core has its core sections enclosed in an annular aluminium box, in which they are suitably cushioned and packed in magnesium-oxide powder.

For the main winding on this core two alternative constructions were possible, namely, (*a*) a single-layer winding in the form of one or more parallel spirals of solid copper, built up in sections, or (*b*) a number of parallel pairs of pancake coils of a relatively thin conductor. Winding (*a*), with which an experimental set of reactors was built, is much the easier to manufacture, but calculation showed that the eddy-current losses in the deep conductors accounted for about 0·5% reduction of the overall efficiency. With type (*b*), on the other hand, the eddy-current losses can be made negligible and the normal I^2R losses lower. The pancake-coil construction (Fig. 11) was therefore adopted in the end, the manufacturing difficulty being surmounted by designing a special toroidal winding machine (Fig. 12), due to Mr. J. H. Cribb.

In addition to the main winding, each comreactor carries three small auxiliary windings of insulated wire, for premagnetization and control. The reactors are enclosed in aluminium casings and cooled by a forced air draught.

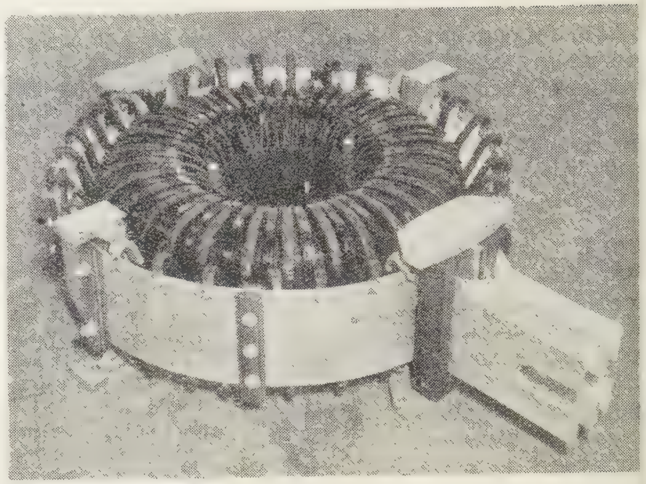


Fig. 11.—Commutating reactor.

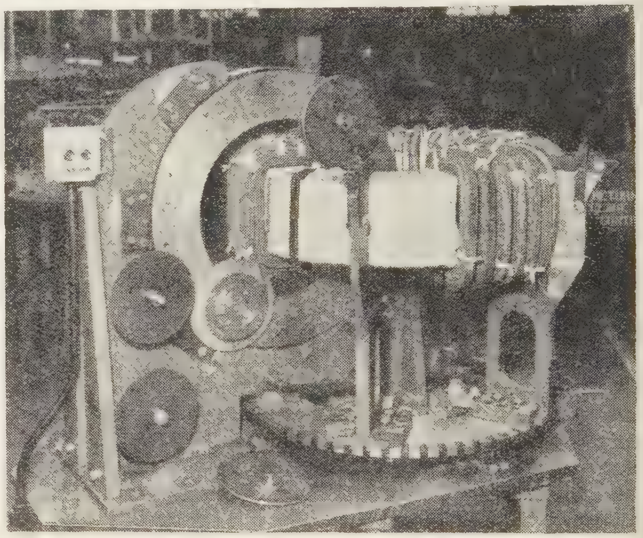


Fig. 12.—Winding comreactor by special toroidal winding machine.

(3.4) Premagnetization of Comreactors

(3.4.1) Main Requirements.

Fig. 13 shows on an enlarged scale the magnetization curves of a comreactor in the unsaturated region. When the load current falls to the neighbourhood of zero, flux change in direction LM will take place during the opening step, corresponding to the commutating voltage being absorbed during this time across the reactor. Conversely, during the closing step the flux will change from an adjustable point such as N to the saturation flux value at P.

Consider first the opening step; if there were no premagnetization the current in the main winding would have to assume a small negative value during the opening step, and if the contact opened at some such point as Q the current broken by it would correspond to RQ. A small constant premagnetizing field OT is, however, applied from an auxiliary source, as a result of which the current to be broken is changed to the smaller and positive value SQ. The opening-step current flows into the by-pass circuit when the contact opens, so the opening step does not come to an end at that instant, and the initial recovery voltage across the contact is low.

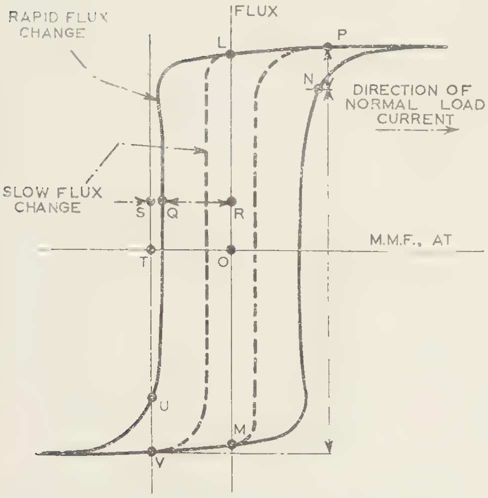


Fig. 13.—Magnetization curves of comreactor.

Since the by-pass circuit accepts current only in the positive direction (see Section 3.6), the flow of opening-step current must cease when the flux has changed to point U, and it might be thought that at the end of the opening step the reactor would thereby be left at this rather uncertainly determined flux. This, however, is not the case, for the following reason. The curves indicated by the full lines in Fig. 13 correspond to the rapid rate of flux change that occurs during the opening step, and the corresponding curves for slow flux change are shown by the broken lines. It will be seen in Section 3.4.2 that after point U has been reached there is a short period during which neither the main nor any of the auxiliary windings is producing any further flux change. The conditions therefore have to revert to those of the broken curve. In other words, the flux changes (as the eddy currents in the core material decay away) from U to the saturation value V.

The flux remains at this latter value until an impulse from the premagnetizing circuit shifts it to a new position N in readiness for the next closing step. The volt-seconds absorbed in (and consequent duration of) the closing step correspond to NP; and thus by varying the position of N the output direct voltage can be varied.

The magnetization curve at N is too nearly vertical and too much dependent on the rate of flux change to enable the flux to be brought to the value at N by mere application of a given m.m.f. Therefore, just before the start of the closing step an adjustable impulse of volt-seconds must be applied by the premagnetizing circuit to an auxiliary winding on the reactor so as to shift the flux from V to N.

(3.4.2) D.C. and A.C. Premagnetization.

The constant negative premagnetizing field OT is easily provided by applying direct current from a separate source to d.c. premagnetization windings on all the comreactors in series, with a regulating rheostat and a large inductance in series to smooth out induced ripple.

To supply the adjustable impulse of volt-seconds, a new circuit* was devised, which makes further use of the properties of sharply saturable reactors.

Consider the circuit shown in Fig. 14(a), in which the two saturable reactors L_{2a} and L_{2b} are equally presaturated with direct current in opposite directions. At the instant W in Fig. 14(b) both reactors are saturated, and the current i is limited by L_1, so it rises in the positive direction. At X, when i has risen to

* READ, J. C., and SMITH, D. R.: British Patent 713968.

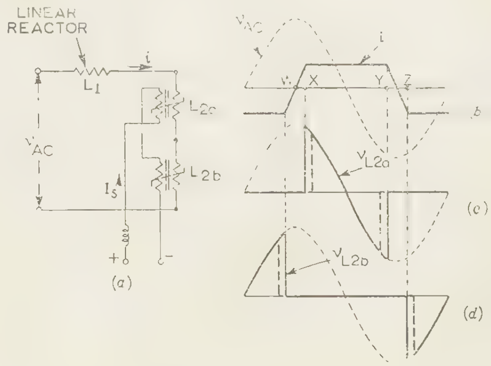


Fig. 14.—Circuit for producing voltage impulses.

the value at which its m.m.f. in L_{2a} just counter-balances the d.c. premagnetizing field, L_{2a} becomes no longer saturated. Therefore, from the instant X onwards, L_{2a} absorbs practically all the applied voltage, while i remains constant. This state of affairs continues until the time integral of the voltage across L_{2a} has returned to zero, i.e. until instant Y. The current i is then again limited by L_1 for a brief period, until at Z it has reached a sufficient negative value to unsaturate L_{2b}. The voltage across L_{2a} is therefore as shown by the full line in Fig. 14(c), and that across L_{2b} as shown in Fig. 14(d). If the direct saturating current I_s is increased, these voltage waveforms become modified as shown by the broken lines.

The positive half-wave of v_{L2a} is therefore of the type required, namely a voltage impulse that can be applied to an auxiliary winding on the comreactor so as to shift the flux from V to N in Fig. 13, this voltage impulse being adjustable in area (by varying the saturating direct current I_s) but always terminating at the same instant. The a.c. premagnetization windings on two comreactors 180° apart are therefore connected respectively across L_{2a} and L_{2b}, with selenium rectifiers in series with them.

However, the voltage produced in the comreactor by the main circuit during the opening step would induce current in this a.c. premagnetizing circuit (since it acts in the conducting direction for the selenium rectifier), i.e. the comreactor would act merely as a transformer with short-circuited secondary. This difficulty is overcome by adding a further saturable reactor, L_3, in series as shown in Fig. 15. L_3 is designed so that its saturation volt-

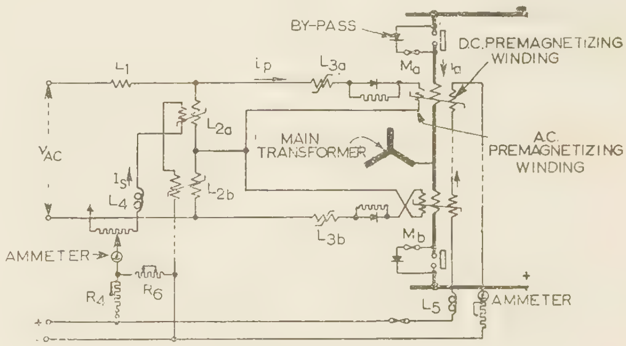


Fig. 15.—Method of premagnetizing comreactors.

seconds are slightly greater than the saturation volt-seconds of the a.c. premagnetizing winding of the comreactor M, but it has a much larger number of turns. Consequently, when the opening-step voltage appears across the comreactor it can induce only a negligible current (the unsaturated magnetizing current of L_3) in

the premagnetizing circuit, and it changes the flux in L_3 from remanence (i.e. practically from saturation) in the one direction to something a little short of saturation in the other direction. Later in the cycle, when L_{2a} produces its positive voltage impulse, this impulse first completes the saturation of L_3, and only then proceeds to change the flux in the comreactor from V to N. Still later in the cycle, while the comreactor is saturated by the main load current, the negative portion of v_{L2a} shifts the flux of L_3 back to saturation in the original direction, in readiness for the next cycle; and in the absence of resistance it would have exactly the value needed for this purpose. A slight compensating correction in this process is required, since the resistance drop in the premagnetizing circuit contains a d.c. component; this correction is supplied by the selenium rectifier.

The complete working of the a.c. premagnetizing circuit is shown in Fig. 16. This diagram can be derived by considering

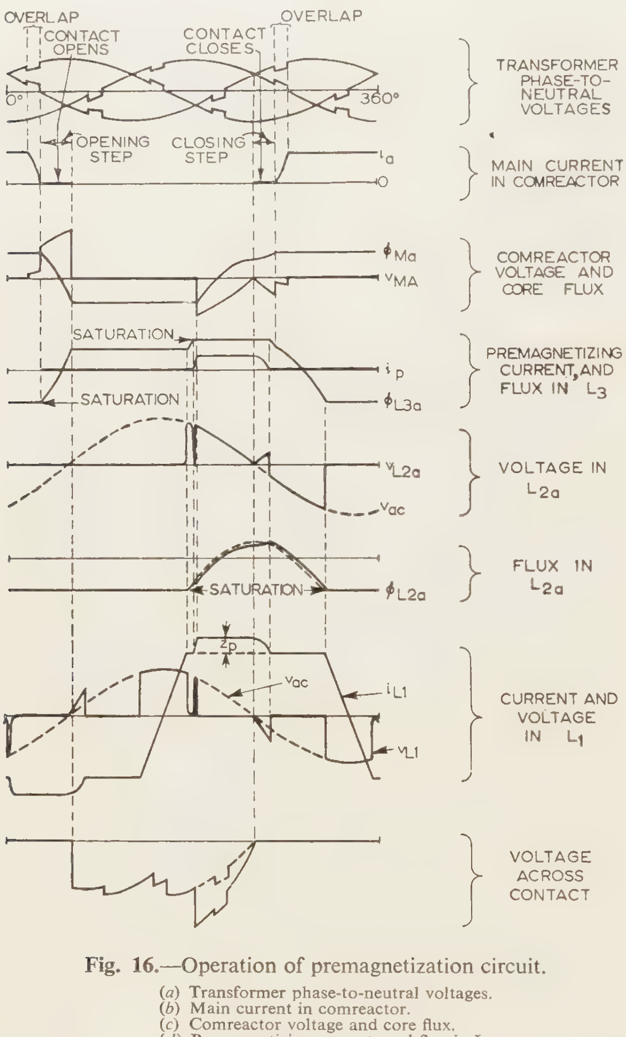


Fig. 16.—Operation of premagnetization circuit.

(a) Transformer phase-to-neutral voltages.
(b) Main current in comreactor.
(c) Comreactor voltage and core flux.
(d) Premagnetizing current, and flux in L_3.
(e) Voltage across L_{2a}.
(f) Flux in L_{2a}.
(g) Current and voltage in L_1.
(h) Voltage across contact.

the entire circuit conditions during each successive section of the cycle, starting from the left-hand side and assuming ideally rectangular B/H loops for L_2, L_3 and M. The waveforms in practice approximate closely to those shown in Fig. 16, except for a small amount of rounding due to departure from this ideal B/H characteristic.

The premagnetization circuit thus fulfils the requirements put forward in Fig. 13, with negligible loss and with simple components having indefinitely long life. The d.c. premagnetization of the comreactors serves to adjust for minimum opening-step current, and can be set once for all. The control current I_s flowing through L_4 (Fig. 15) corresponds to the field current of a generator, and increasing or decreasing it by means of the rheostats provided raises or lowers the output voltage of the rectifier.

(3.4.3) Constant-Current Control.

The rectifiers are designed to operate in parallel on the d.c. side with a very large installation of motor convertors. In the event of a change of alternating supply voltage a considerable change would occur in the load distribution between the contact rectifiers and the motor convertors, owing to the difference between their characteristics. To correct this, each rectifier is equipped with an automatic constant-current control, which is effected through the motor-operated rheostat R_6 (Fig. 15). The operating motor of R_6 is actuated by a current-measuring relay, whose coil is fed by a magnetic amplifier controlled by the shunts in the rectifier output circuit. The constant-current control operates over only a limited range; operation of the tap-change gear, and phase-control of voltage over a wider range, remain manually operated.

(3.4.4) Flattening Circuits.

The current flowing in the contact (and subsequently in the by-pass circuit) during the opening step corresponds to SQ in Fig. 13, and would thus be approximately of the waveform shown by the full line in Fig. 17(*a*) if no further corrective measures were taken. This current, however, is reduced by connecting what has been termed a flattening circuit across one of the auxiliary windings on the comreactor. This draws a transient current during the opening step, and so reduces the step current to the value shown by the broken line in Fig. 17(*a*), i.e. to a lower and more constant (but still positive) value. The use of the flattening circuit is justified by the importance of low contact current at opening, and by its small size and cost.

The circuit used is shown in Fig. 17(*b*). The selenium rectifier serves to prevent the flattening circuit from being influenced by the comreactor voltage during premagnetization and closing step. Circuits R_xC_x and LR_yC_y draw currents of the waveforms shown in Fig. 17(*c*), which vary according to the resistance adjustments. The adjustments required, which can be made once for all, vary according to the slight variations that occur in the exact form of the B/H loop, and the effects of the two adjustments are obvious. R_z serves only to discharge the condensers in readiness for the next cycle, and it has a high value so as to have little effect on the waveform.

The compensation effected by the flattening circuit varies somewhat with $(\alpha + u)$,* because the comreactor voltage varies with $(\alpha + u)$; but in practice the flattening circuit can be adjusted to be satisfactory over the normal working range, and to give a reduction of 2 or 3 to 1 in the opening-step current at the retardation angle and load at which the rectifier usually operates.

(3.5) Automatic Overlap Control

As explained in Sections 3.1 and 3.2, the instant of contact opening is varied, practically independently of the instant of closure, by an adjusting mechanism which both rotates the driving motor and changes the effective push-rod length by means of the overlap-control shaft. This combined mechanism is operated by a motor with reversing contactors, controlled by a relay. It is next necessary to consider how to actuate this relay.

* See Fig. 2.

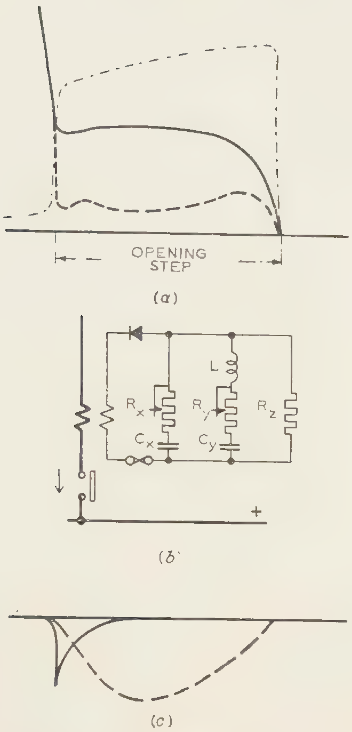


Fig. 17.—Flattening circuit.

(a) Effect of flattening circuit.
—·—· Comreactor voltage.
——— Step current without flattening circuit.
— — — Step-current with flattening circuit.
(b) Flattening circuit.
(c) Circuit waveforms.
——— Current in R_xC_x.
— — — Current in LR_yC_y.

A common method is that shown in Fig. 18(a), i.e. the relay neasures mainly the volt-seconds that appear across the com-eactor from the commencement of the opening step to the nstant of contact opening, and thus it is able to hold constant he shaded area shown in Fig. 18(b). This well-known scheme not only corrects for variations in the position of the opening tep due to change of load, etc., but also largely detects and corrects for changes of contact timing due to mechanical causes, thermal expansion, and gradual change of the contact faces due to the passage of load current through them. Unfortunately the current supplied to the relay coil is broken by the main synchronous contacts without the aid of by-pass circuits, and necessarily is not negligible by comparison with the current and voltage that the contacts can break without sparking.

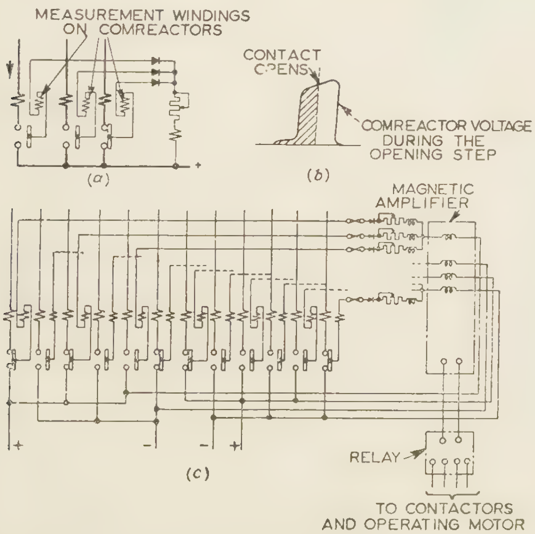


Fig. 18.—Automatic control of contact timing.

In consequence, a modified scheme was adopted, as shown in Fig. 18(c). The relay is actuated through a magnetic amplifier, thereby greatly reducing the current broken by the main contacts. Furthermore, the magnetic amplifier is controlled from all 12 contacts, and thus it averages the effects of any transient mechanical irregularities of the timing of particular contacts, e.g. due to flaking of the contact faces. The relay is of the quiescent type, with a snatching device, as developed for the voltage control of large alternators.

During starting, the contact timing is set at a fixed position, and the automatic overlap control is rendered operative only after the contacts have been lowered to the running position.

(3.6) By-pass Circuits and their Effect on Method of Starting

The by-pass circuit, which in effect is always connected in parallel with the contact, provides a low-impedance alternative path for the current when the contact opens, and thus keeps the recovery voltage across the contact down to only a few volts until the end of the opening step.

Much ingenuity has been expanded on by-pass circuits, and all those hitherto used have disadvantages of one kind or another. The simplest and original type is a condenser across the contact, but this under some conditions gives rise to troublesome oscillations, and it may considerably increase the spark at contact closure. A resistor (of suitable value and connection so that it can also serve to premagnetize the comreactor) provides a simple scheme that avoids these objections, but it gives excessive power loss and provides correct compensation only at one setting. Ideally a simple selenium or gas-discharge rectifier across the contact would be effective, but in practice their forward-voltage drop is too high for the contact to break without sparking. Various methods of biasing such rectifiers (either from a separate source or by self-biasing methods that utilize the inverse voltage across the contact) have been devised, but they mostly involve appreciable loss, are affected by ageing in the case of selenium rectifiers, and are difficult to make of sufficiently low inductance. Equal limitations apply to methods of injecting a compensating current through the contact that is about to open.

The very recent development on a commercial scale of power sizes of germanium diodes has now enabled this problem to be solved in a manner which, while not new in principle, is much better in practice (Fig. 19). This is not only simpler than previous

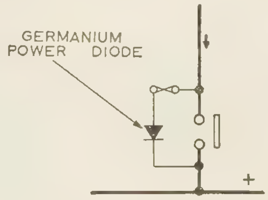


Fig. 19.—By-pass circuit.

schemes, but the low forward-voltage drop and high permissible inverse voltage of the germanium element, and the low stray inductance which is made possible by the smallness of its dimensions, mean that the recovery voltage across the contact is very low indeed.

Two other important advantages can be derived from the use

of the rectifier type of by-pass circuit, and are particularly easily realized when this is of the germanium type. The first is that directly the voltage of the incoming phase exceeds that of the phase already carrying current the closing step commences at once, before the contact closes, owing to the closing-step current flowing initially through the germanium rectifier. Consequently the voltage across the contact during closing is merely the small forward drop across the germanium rectifier, and thus sparking at contact closure is practically eliminated, and also it is not necessary for the step current to be particularly low during the closing step. The latter point is useful, because very low closing-step current is difficult to achieve, owing to the variation of width of the B/H loop that occurs with varying rate of change of flux, and because it is no longer necessary to use extremely thin core material in the comreactor for producing the closing step.

The second advantage is in connection with the method of starting. In the conventional method shown in Fig. 2 a starting resistor is temporarily inserted in series with the transformer during switching on, since the initial inrush current would otherwise cause prohibitive sparking at the main contacts. Whether in the h.v. or l.v. circuit, the short-circuiting switch for this resistor is a bulky and costly item, especially if electrically operated. With the by-pass circuit as shown in Fig. 19 a different method of starting is possible. During switching on, all the moving contacts are simply lifted clear so that they do not close at all, and the current (which at this stage is only that taken by the base-load resistor) flows through the by-pass rectifiers. After this the contacts may be lowered without haste to their normal working position. The starting resistor and its short-circuiting switch are eliminated.

This leads to a further substantial simplification. It means that the driving motor of the mechanical unit need not be already running synchronously at the instant of switching on, so the step-down transformer which supplies this and the other auxiliaries can then be fed through the same oil switch as the main transformer, as shown in Fig. 7.

(3.7) Protection

Fig. 20 shows a cross-section of one of the high-speed short-circuiters, which are connected as near as practicable to the contacts of the mechanical unit, two on each side. Each short-circuits three incoming phases to their corresponding d.c. busbar

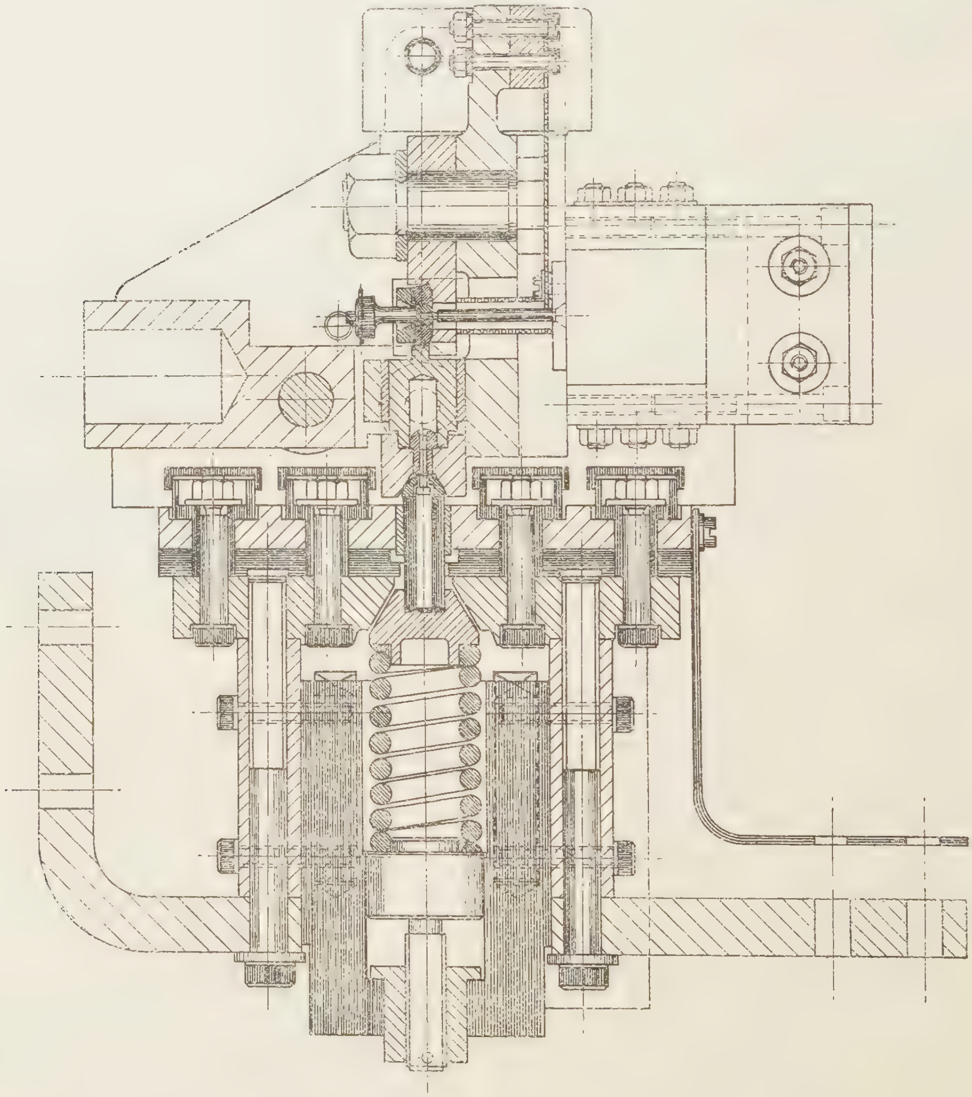


Fig. 20.—High-speed short-circuiter.

thus providing a shunt path across each contact, and at the same time positively short-circuits the a.c. and d.c. systems.

Each high-speed short-circuiter comprises three contacts spring-loaded to the "make" condition. Under normal conditions these contacts are held open by a bridge piece and a single toggle mechanism. The toggle is held a little short of "line dead centre" by means of a permanent magnet. The application of a tripping pulse from the impulse transformer to a winding on this magnet releases the toggle, allowing the contacts to close at high speed under the action of their loading springs.

These devices have been designed to operate in about 1 millisec. It is also necessary that after the contacts have closed there should be no suspicion of bounce, otherwise there is very grave danger of welding taking place. Fig. 21 is a combined oscillogram showing the actual speed of operation and the making of a 3-phase short-circuit.

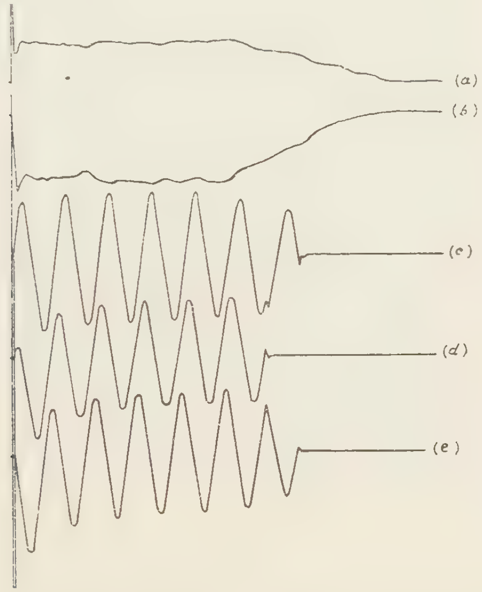


Fig. 21.—Operation oscillogram of high-speed short-circuiter.

(a) Trip coil, 1 volt/cm.
(b) Trip coil, 8 amp/cm.
(c) $R = 54$ kA/cm.
(d) $Y = 72$ kA/cm.
(e) $B = 56$ kA/cm.

This initial contact protection by the high-speed short-circuiter is followed by interruption of the d.c. short-circuit by conventional high-speed circuit-breakers of the trip-free reverse-current type. Each of these carries a normal full load current of 3 750 amps, four being connected in parallel. The four main connections to these circuit-breakers are nominally insulated from each other for the maximum length, in order to utilize the series busbar voltage-drop to assist in current sharing equally among the four circuit-breakers.

Opening of the oil circuit-breaker is operated by a shunt tripping supply connected through auxiliary contacts on the high-speed short-circuiters and circuit-breakers, and backed up by instantaneous overload protection in the normal way.

In the installation at the chemical works the prospective direct short-circuit current of the plant is extremely high, but actual short-circuit tests undertaken directly across the busbar resulted in a current of the order of 60 kA when interrupted in a time of about 0·015 sec, the recovery voltage amounting to approximately 1 kV.

It is an inherent feature of contact rectifiers that, if the main circuit-breakers were simply opened as quickly as possible without going through the proper shutting-down sequence, a backfire would occur, with consequent possibility of damage to some contacts during the brief time before the circuit is completely opened. For this reason automatic tripping of the circuit-breakers is confined to those protective devices that would indicate need for instant action. Devices of a less urgent nature operate an alarm.

(3.8) Supervision of Contact Timing

Much consideration was given to the relative merits of an oscillograph or voltmeters connected to give an indication for each contact. The voltmeter scheme has an apparent simplicity, but the information it can give as to what is happening is very limited, whereas the oscillograph can readily show in detail the conditions at both "make" and "break," or at any other part of the cycle or any part of the circuit, and can also better show any transient variations. It was therefore decided to provide a portable single-beam oscillograph, together with plug-and-socket connectors and a selector switch enabling it to be connected across the measurement winding of each comreactor in turn. In addition, a portable "dwell meter" of the voltmeter type is provided, and can be connected by plug-and-socket connectors across any main contact (when the mechanical unit is running on the auxiliary supply, with main contacts dead), to give more exact measurement of contact timing when new contacts are fitted.

The most important use for the oscillograph is to check the instant in the opening step at which the contacts part. Hitherto a common method of doing this has been to observe the comreactor voltage during the opening step, and usually a small abrupt change of voltage then shows the point of contact opening. However, with these sets the combined operation of the premagnetization, flattening circuit and by-pass circuit proved so effective that it was totally impossible to find this point when examining the voltage across the main winding of the comreactor. The resulting inconvenience was not trivial, for such supervision cannot be dispensed with. For this reason the oscillograph is arranged instead to observe the voltage across the measurement winding, since the very small current flowing in this winding to the automatic overlap control (Fig. 18) has to be broken by the contact without the benefit of a by-pass circuit, and consequently an easily visible "blip" occurs in this voltage trace when one side of the contact opens.

(3.9) Plant Layout

In the sets subsequent to the prototype the need for oversize components and ease of modification no longer applied, and it

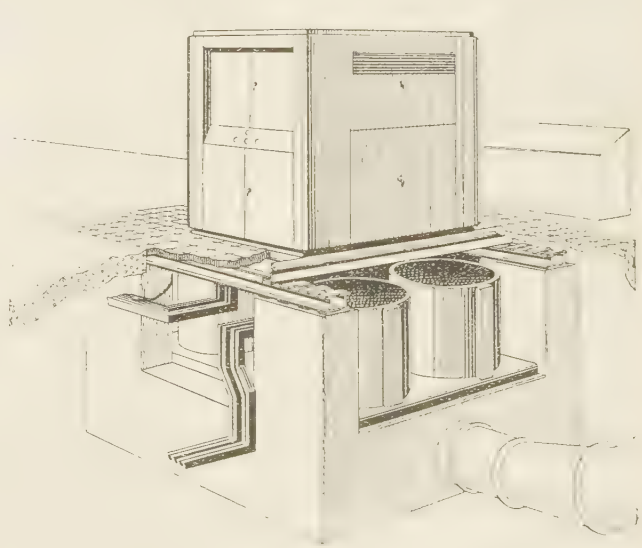


Fig. 22.—Isometric view of assembly of mechanical unit and comreactors.

was therefore possible to aim at a neater arrangement, and in particular to reduce to the minimum the bulky low-voltage a.c. copper-work. It was felt unwise to put the comreactors inside the tank of the main transformer, as the latter already contained complication enough and any saving would have been trivial; and it seemed to the authors that there were advantages in introducing the heavy-current connections to the mechanical unit from beneath, half on each side, and in adopting a vertical-axis arrangement for the comreactors. These considerations led to locating the mechanical unit immediately on top of the comreactors (but supported independently of the latter), thereby giving very short copper-work and low loss in the connections. Installation of the comreactor assembly in the basement is provided for by a removable section of floor. Figs. 22 and 23 show the arrangement.

magnetization system and by-pass circuits have been found to operate almost exactly as predicted by theory. Fig. 24 shows typical waveforms which illustrate this.

In the prototype a small constant load unbalance was found to exist between the two apparently identical halves of the equipment. This unbalance is due to variations of the *B*/*H* loop between different core sections in early consignments of the comreactor core material, and it is not sufficient to prevent the set as a whole from delivering its rated total output. In the 1955 sets better and more uniform *B*/*H* characteristics have been obtained, and in addition there is a trimming adjustment.

A point found by test is that, even with 6-phase operation, it is not necessary from the aspect of commutation to include a large inductance in the d.c. circuit, but when working on a low-inductance back-e.m.f. load a special mode of commutation occurs at low currents, and stable operation is maintained even below the point where the output current becomes discontinuous.

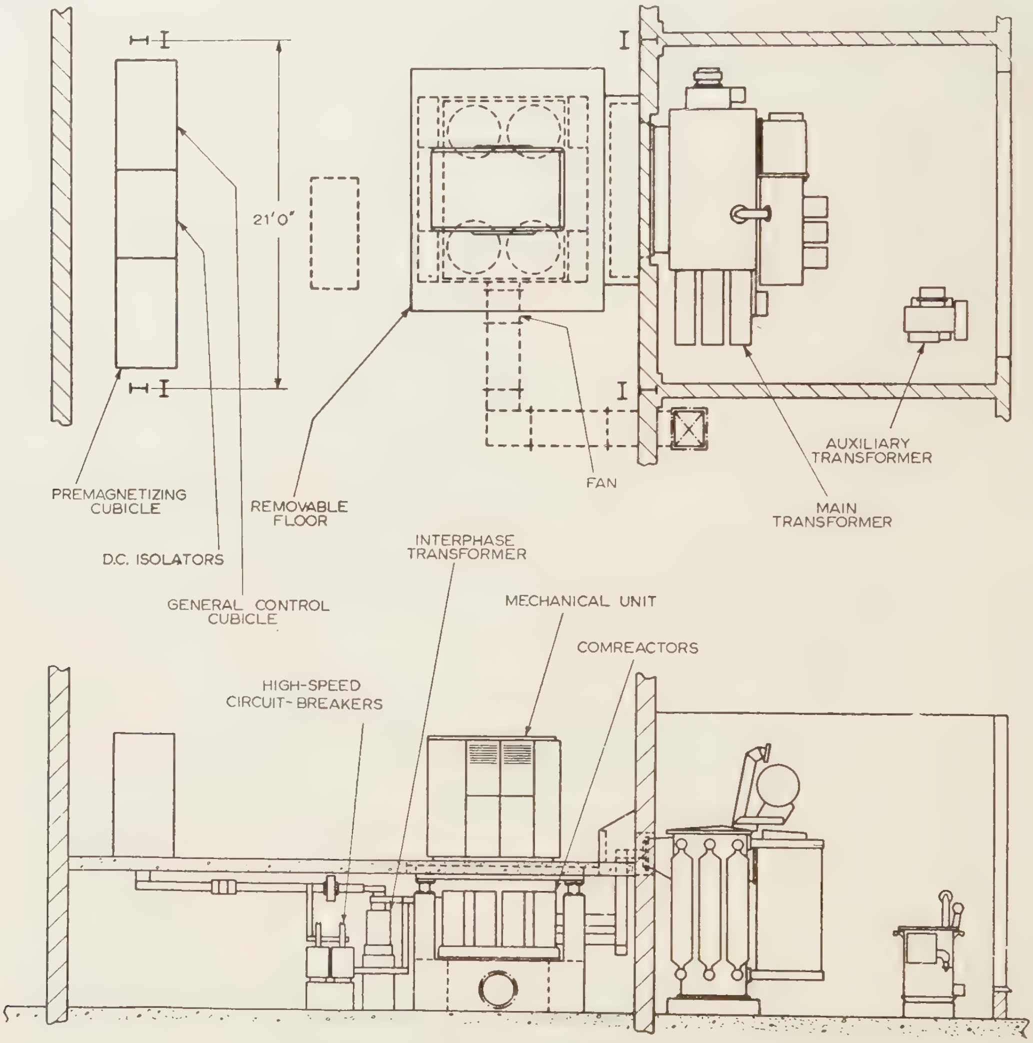


Fig. 23.—Layout.

(4) OPERATING RESULTS

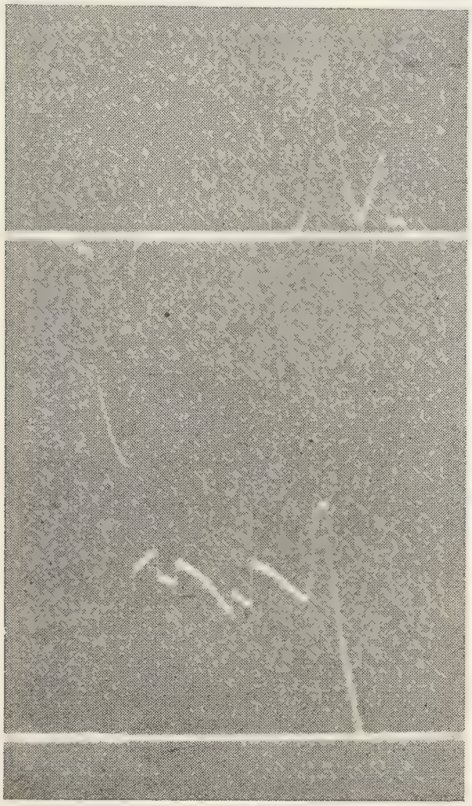
The prototype set has been in commercial service for about a year, and the first of the subsequent sets has received preliminary tests. Experience, although so far short, seems sufficient to indicate that the design is generally on sound lines and no major difficulties are likely to arise. The various differences from established practice appear to have been justified.

Dealing first with the electrical side, the comreactors, pre-

With regard to the mechanical side, a series of tests was undertaken on a single-phase model and these showed that some of the conventional arrangements, such as ball and roller bearings, etc., gave trouble under the very severe duty they were called upon to discharge.

The original design of contact push-rods included a hardened-

teel end. This was later abandoned in favour of insulated ush-rods, as a number of difficulties were encountered from lectrical burning on backfire.



ig. 24.—Voltages across comreactor (upper trace) and contact (lower trace).

The early experiments used conventional forms of contact, and hese indicated the necessity for some few hours' running in rder that the contacts should bed down and find their correct ositions before operating on full load. Failure to observe this sually resulted in premature backfiring, owing to the pip-and-rater formation of the contacts falling out of line. At a later ate experiments were conducted with guided contacts; although is feature would appear not to add materially to the actual ngth of life, it resulted in alignment being sustained over the hole range of operation, which in turn enabled the unit to go n load much more rapidly.

During early running the design of short-circuiters fitted to e prototype was a frequent source of backfires, owing to the olding coils of the magnetic latch being electrically energized om batteries. These batteries had a fairly high rate of dis-harge, and the problem of ensuring that the short-circuiters ere critically latched under varying states of charge of the attery led to the device being redesigned and the electromagnet eing replaced by a permanent magnet.

The contact life in service, as with all contact rectifiers, will epend only partly on the design features, and is much influenced so by the exact adjustments adopted and the extent to which the onditions of operation approximate to those assumed in making e adjustments. As regards the features that are under the esigners' control, the unusually low contact current and oltage at both make and break have already been pointed out. perating experience of a non-experimental type with the proto-pe has so far been too short to establish the maximum contact life obtainable, but the evidence indicates that it is likely to be at least equal to that normally obtained with such rectifiers.*

The overall regulation characteristic shows practically no light-load voltage rise attributable to incomplete saturation of the comreactor cores at light loads, and it would thus appear that the H.C.R. alloy cores can be regarded as totally saturated above something of the order of 10 oersteds. At heavier loads the regulation characteristic actually obtained is affected, however, by the fact that the natural regulation is partly neutralized by a small variation of closing-step length that occurs with load or supply voltage. For example, when operating on a practically infinite d.c. busbar and without constant-current control, 1% change of a.c. supply voltage produces 10–15% change of load current.

The power factor depends on the length of closing step in use, which is adjustable. With a reasonable minimum value of closing step the power factor obtained is approximately 0·88.

The efficiency is the most important of the performance figures. The estimated overall efficiencies of the 1955 sets, as determined by the usual method of summation of measurable losses and including the transformer stray loss as given in B.S. 1698 but excluding connections, is given in Table 1.

Table 1

Overall Efficiency on Maximum Tap, 4050 kW, 15 kA, 270 volts

Losses	kW
Main and interphase transformer core losses	19·2
Main and interphase transformer copper plus stray losses	43·1
Comreactors	34·0
Contacts	5·6
Driving motor and lubricating unit	3·7
Cooling fans for mechanical unit	2·1
Cooling fans for comreactors	1·5
Premagnetization	5·2
By-pass circuits	0·04
Total	114·44
Input	4164
Overall efficiency	97·25%

(5) ACKNOWLEDGMENTS

The development of the contact rectifier was undertaken at the request of the Imperial Chemical Industries, Ltd., for their electrolytic service.

The initiation and the rapidity of this development were due to Mr. T. E. Houghton, Division Director and Power Department Manager, General Chemicals Division, Imperial Chemical Industries Ltd., and Mr. K. R. Hopkirk, Director and Chief Mechanical Engineer, The British Thomson-Houston Co., Ltd., to whom we are indebted for permitting this publication. In writing the paper the authors do so on behalf of many engineers who made essential contributions to the project, particularly Dr. H. H. Scholefield (The Telegraph Construction and Maintenance Co. Ltd.), Mr. D. R. Smith (now with Associated Electrical Industries and John Thompson, Industrial Nuclear Energy Group), and Messrs. T. B. Hughes, V. E. Milward, S. J. Pearson, J. W. Powell, and J. Rose.

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(7) APPENDICES

(7.1) Symbols Used

V_{d0} = Ideal light-load output direct voltage, with no voltage drops ($\alpha = 0$, $u = 0$), volts.
V_c = R.M.S. value of commutating voltage (Fig. 2).
I_d = Rated output direct current, amp.
f = Supply frequency, c/s.
Δ_{ts} = Duration of opening step, at peak commutating voltage $V_c\sqrt{2}$, sec.
N = Number of turns in main winding of comreactor.
S_c = Effective core section of comreactor, in².
B = Flux density in core at knee of saturation curve, lines/in².
$A = \dfrac{\text{(Effective section of air-flux circuit)}}{\text{(Effective section of core)}}$
D = Mean diameter of magnetic circuit of comreactor, in.
x, y, z = Winding dimensions (Fig. 25), in.

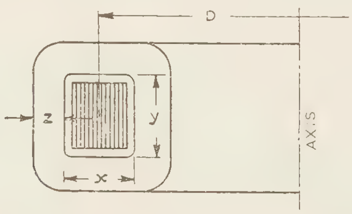

Fig. 25.—Comreactor winding dimensions.

L = Saturated inductance of main winding, henrys.
X_R = Percentage saturated reactance, i.e. amount of percentage reactance of main transformer (referred to primary-line apparent power at rated load) that would produce same inductive direct voltage drop as saturated comreactors.
V_R = Component of inductive direct-voltage regulation drop produced by saturated comreactors, volts.
H_c = Coercive force of comreactor core (at actual rate of flux change during opening step), amp-turn/in.
I_s = Opening-step current in absence of premagnetization and flattening circuits (RQ in Fig. 13), amp.
N_t = Total number of conductors, such that no circulating currents can flow (= turns per pancake × number of pancake coils).
a = Radial thickness of conductor, in.
b = Width of conductor in direction tangential to air flux, in.
ρ = Resistivity of conductor, microhm-in.

(7.2) Determination of Comreactor Size

The product, turns × core section, is given by

$$NS_c = \frac{\Delta_{ts}V_c}{B\sqrt{2}} \times 10^8$$

$$= K_1\frac{\Delta_{ts}V_{d0}}{B\sqrt{2}} \times 10^8 \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $K_1 = \pi/(3\sqrt{2})$ for bridge connection [Fig. 4(*b*)] . (2)

$K_1 = \pi\sqrt{(2)}/3$ for double-star connection [Fig. 4(*a*)] (3)

$K_1 = \pi/(6\sqrt{2})$ for polygon connection (Fig. 3) . (4)

The "air" inductance of the saturated comreactor is

$$L = 1{\cdot}012 \times 10^{-8}\frac{N^2AS_c}{D} \quad . \quad . \quad . \quad . \quad (5)$$

where

$$A = \frac{xy + \frac{2z}{3}(x + y) + \frac{\pi}{9}z^2}{S_c} \quad . \quad . \quad . \quad . \quad (6)$$

The corresponding percentage reactance is

$$X_R = K_2\frac{fLI_d}{V_{d0}}$$

$$= 1{\cdot}012 \times 10^{-8}K_2\frac{fN^2AS_cI_d}{DV_{d0}} \quad . \quad . \quad . \quad (7)$$

where $K_2 = 1\,200$ for bridge connection [Figs. 6(*a*) or 6(*b*)] . . . . (8)

$K_2 = 300$ for double-star connection [Fig. 4(*a*)] . (9)

$K_2 = 1\,600$ for polygon connection (Fig. 3) . . (10)

Hence, from eqns. (1) and (7), the comreactor core volume πDS_c is

$$\pi DS_c = 1{\cdot}59 \times 10^8K_1^2K_2\frac{fA(I_dV_{d0})\Delta_{ts}^2}{B^2X_R} \quad . \quad . \quad (11)$$

and the step current is

$$I_s = 2{\cdot}25K_1K_2\frac{fAI_dH_c\Delta_{ts}}{BX_R} \quad . \quad . \quad . \quad . \quad (12)$$

Since little variation of A is possible, eqns. (11) and (12) show the very interesting result that, for a given connection, once the step length and percentage reactance have been determined, the core weight (which mainly determines the cost) and the step current are practically fixed, the core weight being proportional to the power output and the step current proportional to the current output.

However, in practice Δ_{ts} and X_R are interdependent, as the step length must be made suitable for the chosen total percentage reactance (including X_R), in order that the instant of contact opening may remain inside the opening step if the load suddenly

:hanges by some desired amount mI_d. Only part of the total tep length can be regarded as available for this latter purpose. This part must be made equal to the change in the duration of the overlap, u, that would be produced (at peak commutating voltage) by the sudden load change mI_d. The formulae which express his, while obvious, do not give equations for comreactor size or step current that are sufficiently simple to be useful for purposes of general comparison. However, it can be seen that the elationship between Δ_{ts} and X_R is such that the core weight is nore nearly proportional to Δ_{ts} than to Δ_{ts}^2; the step current is nore nearly independent of Δ_{ts}; and no direct comparison can be made from the formulae between the comreactor costs and step currents as affected by the choice of connection.

With single-way comreactors, Δ_{ts} also fixes the maximum phase delay obtainable by closing-step length. This is given by

$$\cos \alpha_{max} = 1 - 2\pi f \Delta_{ts} \quad . \quad . \quad . \quad . \quad (13)$$

e.g. if $\Delta_{ts} = 20°$, $\alpha_{max} \simeq 50°$.

The effect of X_R on the inductive voltage regulation is

$$\frac{V_R}{V_{d0}} = K_3 \frac{X_R}{100} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

where $K_3 = \frac{1}{2}$ for bridge or double-star connection [Figs. 6 or 4(a)] . (15)

$K_3 = \frac{3}{4}$ for polygon connection [Fig. 3] . . . . . (16)

The eddy-current loss in the conductors of the main winding (assumed to consist of pancake coils of conductors wound on the flat) is easily calculated for the practical case where the conductor thickness is small enough so that the eddies do not themselves appreciably modify the flux distribution.

It can be shown that

$$\frac{\text{a.c. resistance}}{\text{d.c. resistance}} = 1 + 0{\cdot}282\left(\frac{f}{50}\,\frac{N_t a^2 b}{D\rho}\right)^2 \quad . \quad . \quad (17)$$

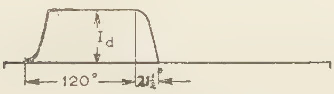

Fig. 26.—Current waveform.

For the current wave shown in Fig. 26, which is fairly typical in the single-way comreactors shown in Fig. 6(b), harmonic analysis gives

h	0	1	2	3	4	5	6	7	8	9	10	11
I_h/I_d	0·333	0·388	0·193	0	0·091	0·070	0	0·045	0·037	0	0·026	0·024

where h is the order of the harmonic.

Now let $I_{nom} = I_d/\sqrt{3}$.

Then for 50 c/s operation of the comreactor shown in Fig. 6(b), with $\rho = 0{\cdot}83$ for copper, we obtain, very nearly,

$$\frac{\text{Total } I^2R \text{ loss}}{I_{nom}^2 R_{dc}} = 0{\cdot}96 + \left(\frac{N_t a^2 b}{D}\right)^2 \quad . \quad . \quad . \quad (18)$$

(7.3) Principal Data*

Rating.

A.C.	3-phase, 50 c/s, 11 kV.
D.C.	15 kA, 220–270 volts.
Overloads	B.S. 1698, Class V.
Phases	12.

* The prototype set differs slightly in a few details.

Main Transformer.

Primary connection	Double delta.
Secondary connection	Delta and star.
Secondary line voltage	192–240 volts.
Primary-line apparent power on maximum tap	4 900 kVA.
Reactance on maximum tap	4·3%.

Mechanical Unit.

Contacts	12, silver.
Contact cooling	Forced filtered air.
Contact current	7·5 kA peak, 4 333 amp r.m.s.
Contact spring pressure	200–250 lb.
Contact area, each	0·65 in².
Throw of eccentric	±0·077 in.
Normal contact lift	Approximately 0·08 in.
Contact timing	0·75° per 0·001 inch lift.
Normal range of contact dwell	180°–145°.
Synchronous driving motor	3 h.p., 2-pole, unexcited rotor, with polarity indicator.
Lubrication	2-stage, forced, temperature-controlled.
Oil-pump motor	1 h.p.
Fan motors	Four 0·5 h.p.
Type of by-pass circuit	Germanium diodes.

Comreactors.

Number and connection	12, single-way.
Current, r.m.s.	4 333 amp.
Net core section	15·3 in².
Mean length of magnetic circuit	66 in.
Saturated reactance, referred to transformer apparent power on maximum tap	7·8%.
Step current, in absence of premagnetization and flattening	Approximately 3·5 amp.
Turns in main winding	16.
Turns in d.c. premagnetizing winding	27 ± 2 and 4.
Turns in a.c. premagnetizing winding	27 ± 2 and 4.
Turns in measurement winding	4, 8 and 16.
Fan motor	2·5 h.p.

Premagnetizing Apparatus.

Maximum total input	5·2 kW, 25 kVA.
Maximum phase control catered for	30° delay.
Maximum d.c. premagnetization of comreactors	0·75 oersted.
Maximum a.c. premagnetization of comreactors	1·4 oersted, peak.
Flattening circuits, R_x [Fig. 17(b)]	0–500 ohms.
C_x	0·5 μF.
L	65 mH.
R_y	0–200 ohms.
C_y	1·6 μF ± 20%.
R_z	2 500 ohms.

Short-Circuiters.

Number	4.
Contacts, each	3.
Minimum operating time	1 millisec.
Trip-coil inductance (each)	Approximately 50 μH.
Minimum tripping current	Approximately 15 amp.
Volt-seconds provided by impulse transformer	0·04 volt-sec.

Miscellaneous.

A.C. overload protection	Instantaneous and inverse time relays.
Auxiliary supply transformer	3-phase 11 000/420 volts, 100 kVA.
Base-load current	15 amp × 2.
Base-load inductance	30 mH each.

DISCUSSION ON "SOME RESEARCHES ON CURRENT CHOPPING IN HIGH-VOLTAGE CIRCUIT-BREAKERS"*

Before the North-Eastern Centre *at* Newcastle upon Tyne 12*th January, the* North-Western Supply Group *at* Manchester 10*th February, the* South-West Scotland Sub-Centre *at* Glasgow 17*th March, the* South Midland Supply and Utilization Group *at* Birmingham 9*th November*, 1953; *the* Mersey and North Wales Centre *at* Liverpool 18*th January, and a* Joint Meeting *of the* Sheffield Sub-Centre *and* North Midland Centre *at* Barnsley 3*rd* March, 1954.

Mr. E. C. Rippon (*at Newcastle*): The conclusion under Section 10 (*p*), that the voltages produced by current chopping are determined by the characteristics of both the circuit breaker and the transformer or reactor, is one of considerable practical importance, and I propose to limit my remarks to this aspect of the problem, with particular reference to power transformers.

The major factor is the available amount of magnetic energy in the transformer for any value of current chopped. The excitation demand of a transformer depends upon its operating flux density, the magnetic characteristics of the core materials and, lastly, the type of tap-changer employed. Other operating considerations usually determine the value of the flux density and the type of core material used in power transformers, hence the method adopted to alter the transformation ratio is probably the only variable in the transformer construction which can influence the value of the switching over-voltages.

Resistors or reactors can be used in on-load tap-changers to limit the circulating current in the transformer windings during transition from step to step. The fitting of mid-point tap-changer reactors to a power transformer may treble its excitation demand when the reactors are energized and the magnetic-remanence characteristic of the combination will differ from that of the power transformer alone. The effect of this change in the magnetic characteristic is clearly indicated in the test results (see Table 6, which compares the measured over-voltages with and without reactors connected to the transformer winding).

Whilst on-load tap-changers of both the resistor and mid-point reactor patterns have been equally satisfactory in operation for a number of years, there has latterly been a tendency to favour the installation of reactor type of gear in preference to resistor. This arises from the fact that resistor-type tap changers are not fully rated and it is essential to de-energize the associated transformer should the tap-changer fail to complete a step.

During the last few years, a new high-speed type of resistor gear has been developed in this country which eliminates the rating difficulties hitherto associated with this type of tap-changer. Apart from current chopping in h.v. circuit-breakers, the installation of high-speed resistor-type tap-changers reduces the overall bulk of transformers so equipped—an important advantage when 3-phase units of the order of 150 MVA are contemplated.

The choice of transformers for installation in future very-high-voltage systems employing air-blast circuit-breakers may well be decided by the type of tap-changers adopted should other measures to reduce over-voltages prove impracticable.

Mr. R. A. Hore (*at Newcastle*): The author has stated that there are still many unexplored aspects of the subject of current chopping. One is the problem of the h.f. oscillations of current and voltage discussed in Section 2.2. The h.f. oscillations are excited by variations in arc resistance, the frequency of the h.f. oscillations being basically determined by the circuit. If any connected apparatus has a natural frequency near to the frequency of arc-resistance variation, dangerous over-voltages may occur, owing to resonance. At least one apparatus failure has been attributed to this phenomenon, and it therefore seems that further investigation of the frequencies produced is desirable. Could the author indicate the present state of knowledge on the causes and frequencies of these oscillations?

I disagree with the author's statement, in Section 9, that current-chopping voltages produced by oil circuit-breakers when switching transformers are relatively small and no action is necessary to reduce them further. A case is mentioned in paragraph 5 of Section 8.2, indicating that high over-voltages are possible owing to multiple current chopping. These over-voltages do not occur very frequently, and it must be emphasized that a large number of shots are desirable to ensure obtaining some approach to the worst conditions in tests of this nature.

With reference to the correlation between measured and calculated values of over-voltage, I disagree with the comment

* Paper by A. F. B. Young (see 1953, **100**, Part II, p. 337).

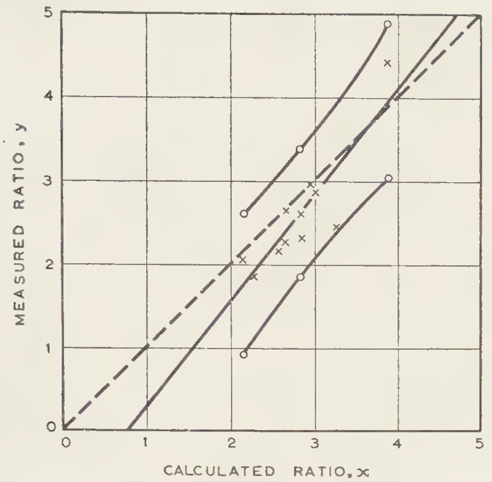

Fig. L

in the last paragraph of Section 4.4.1 that random factors tend to make the practical values lower. Fig. L shows the correlation between the measured voltage ratio and calculated ratio of voltages taken from Table 2. The crosses indicate pairs of values given in the Table. The broken line is the line upon which the crosses should lie if the calculated ratio is equal to the measured ratio. The continuous straight line is the best line through the points shown. The outside curved lines show the limits between which one may expect the measured voltage ratio to lie for any particular calculated ratio, the probability of inclusion being 95%. Calculations of the correlation indicate that the theory developed in the paper accounts for about 88% of the relevant factors, which is a highly commendable achievement. The spread about the best line, however, indicates (a) that further investigation is very desirable, (b) that appreciably higher voltages than those calculated are likely to occur, and (c) that the circuit-breaker gap is at present a very crude voltage-limiting device.

In his introductory remarks the author emphasized the importance of a better understanding and a better control of switching over-voltages as system voltages increase, because at the highest system voltages the insulation as determined by lightning requirements tends to be exceeded by switching over-voltages. From the information contained in the paper and from a consideration of Fig. L it appears either that the circuit-breaker gap characteristics must be improved quite considerably or that some additional provision such as resistance switching must be made to limit more closely switching over-voltages. Whilst admitting the objections to resistors or voltage-limiting devices on a circuit-breaker, one can afford to spend a certain amount of money on such devices if the result permits reducing the insulation level of a system. Of course, if the circuit-breaker can really be made self-limiting without such devices, so much the better.

Mr. D. F. Amer (*at Newcastle*): Some years ago it was said that in the opening of inductive circuits only compressed-air circuit-breakers would cause current chopping; but of recent years current chopping has been examined by numerous investigators when opening appropriate circuits with widely different apparatus, such as relays, small switches, isolators and circuit-breakers of all kinds; and it is now known that almost all circuit-breaking devices that depend on a short arc for breaking the circuit are prone to current chopping. The paper is a most useful addition to the growing volume of information on current chopping in high-voltage circuit-breakers.

I am interested in the surge voltages produced when circuit-breakers for the highest voltages open inductive and capacitive circuits.

So far as inductive loads are concerned, it has been shown by the author that the actual surge voltages can also be chopped or limited by the action of the circuit-breaker, and that this is a characteristic of the circuit-breaker contact gap.

Considered alone, the opening of highly inductive circuits would present no problem; but unfortunately, for efficient opening of long lines and circuit-breaking under asynchronous conditions, conflicting circuit-breaking characteristics are required, and in particular a high breakdown level of the circuit-breaker contact gap.

Much has been said about the use of resistance switching for minimizing over-voltages. Here again the breaking of inductive and capacitive loads and circuit-breaking during asynchronous conditions require conflicting breaking characteristics, which could be provided only if a different value of resistance and a different arrangement of contact gaps were used for each duty. A compromise between these breaking characteristics must exist in any practical circuit-breaker, and although the prospective over-voltages may be reduced by resistance switching, the actual voltages determined by the breakdown of the contacts during the unstable arcing period are not greatly modified from those that can be obtained with circuit-breakers not fitted with resistors.

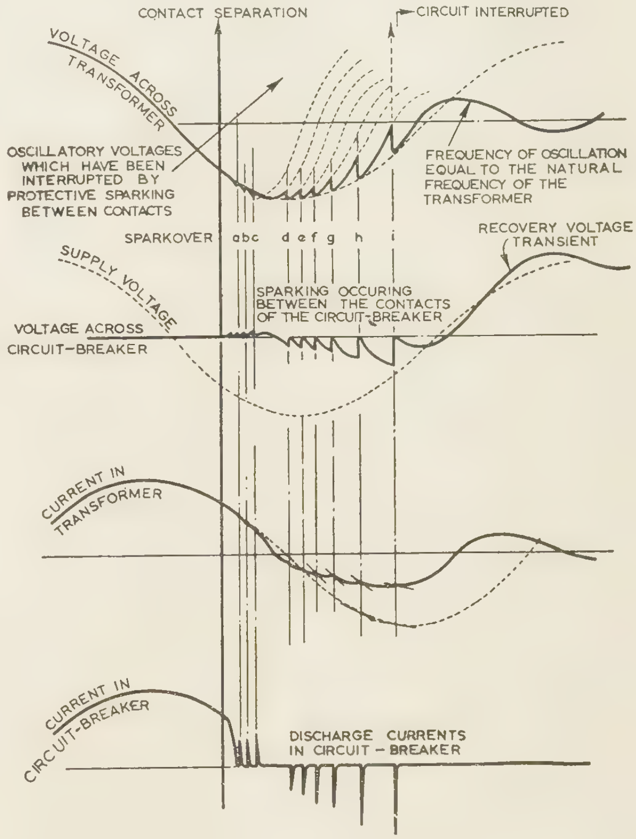

Fig. M

Fig. M shows the form of the current in a highly inductive load. It shows how the current is frequently distorted by the repeated making and breaking of the load by unstable arcing so that current and voltage are almost brought into phase. The voltage across the inductance at the instant of final clearance is therefore generally not as high as one might expect.

Mr. R. Bruce (*at Newcastle*): In the tests on a 45 MVA 132 kV

transformer outlined in the paper, the figures tabulated indicate that peak voltages up to three or four times normal may be obtained owing to chopping of magnetizing current. Such voltages reach the order of 400 kV, and in a few instances during the tests they caused flashover of rod-gaps set at 22 in, across the transformer windings.

The voltages across the transformer windings due to current chopping, without flashover of gaps, are fairly rapid transients, but compared with an impulse wavefront of 1 microsec—which is a necessary basis of winding design for transformers in the impulse-tested class—these transients are slow. Unlike impulse test voltages, therefore, which may produce a widely varying distribution of intercoil voltage throughout the winding, excess voltage, caused by switching, is distributed uniformly between phase and neutral terminals. The intercoil conditions, therefore, are not severe if there is no flashover of rod-gaps. The voltage to earth is of more importance in this respect, but although maintained longer than would be the case with standard impulse voltages, the duration is still very short compared with a.c. test values. From known breakdown characteristics of transformer insulation one would not anticipate difficulty with voltages to earth.

The possibility of rod-gap flashover due to switching is, however, a very different question, since the resulting voltage chop is essentially equivalent to the application of a steep-fronted long-tailed impulse of reverse polarity, superimposed on the linear voltage distribution of the switching transient. This chopping of voltage will thus produce conditions similar in many respects to those encountered in impulse testing of transformers. Present knowledge indicates that gap flashover due to switching surges should be no more onerous than chopped impulse waves, but there is useful scope for further research into this particular problem.

The normal lightning protection in this country is the co-ordinating gap, and it appears that gap flashover due to switching surges in service may occur more frequently than with lightning phenomena.

The transformer used for the tests described in the paper was protected by rod-gaps set at 22 in, which represents a protective level of 80% of the impulse test level of the transformer. It cannot be over emphasized that a protective level of 80% is desirable to give complete service protection of the transformer insulation, whether lightning or switching over-voltages are concerned. The 26 in gap normally employed for 132 kV systems represents a protective level of 90% of the impulse test level of 550 kV, and is open to criticism because of the scanty margin in conjunction with the number of operational flashovers which may occur during the life of the transformer.

Mr. A. C. Ehrenberg (*at Manchester*): The paper is divided into three parts, theory, research, conclusion; in my opinion a fourth should be added, namely measurement and recording. This is really very important; a correct interpretation of oscillograph records in my experience requires a comprehensive knowledge of the circuit technique.

Theory of electric arcs as applied to circuit-breakers is still a speculative matter. In such fields each individual student tends to plough his own furrow and his is always much straighter than the other fellow's. I am in such a position: I do not disagree with what the author says, I just do not like the way he says it. Then having stated a theory I feel it is essential to point out some of its limitations. The thermal clearance theory is fair enough for comparatively small r.m.s. currents, but it does not cover the arc-extinction problems of the commercial circuit-breaker. These devices are not designed for the switching of transformer magnetizing currents only. The interruption of rated short-circuit currents of 10, 15, 20 kA or more brings other phenomena which considerably upset the mathematical approach indicated under Section 13.3. These same remarks I wish to extend to the curves showing gap-breakdown characteristics, namely Figs. 8, 15 and 16; these are very interesting and must cover an immense amount of work, but they must be qualified. They are applicable only to the range of currents considered by the author, and for that matter they are also limited to the specific types of circuit-breaker he used for his investigation. I think it is also necessary to make it clear that there is an upper limit of r.m.s. current above which circuit-breakers will no longer chop, i.e. a given circuit-breaker interrupting an r.m.s. current of 500 amp may chop to some small degree, but when interrupting a current of 1 000 amp, no sign of chopping will be evident for similar circuit conditions. I lay great stress on these qualifying points because the paper is read by engineers less familiar with circuit-breaker performance than the author, and misconceptions are easy enough for those constantly engaged on this subject. After all, the paper is a basic work—an excellent basic work—so let it be enlightening not to the few but to the many.

Research introduces the problem of measurement which is emphasized by high voltage. It is not difficult to record high voltage with a cathode-ray oscillograph, but when this voltage is of an oscillatory nature at high and irregular rate of change, even the natural frequency of the measuring circuit needs consideration. I note from Fig. 3 the high frequency and comparatively large amplitude of the arc current, and I should like to have a circuit diagram and information on the method of measurement. In this respect I should like the author to give some information on the method employed in measuring the arc resistance and also the arc current.

Fig. 4 is supposed to show premature extinction; I cannot read that into this record unless the author assumes that the current should reach zero when the restriking voltage passes through zero.

Fig. 5 is to me the most interesting of records, since it shows post-arc current on an air-blast breaker, and therefore confounds the oft-expressed opinion that air-blast circuit-breakers are not prone to such faults.

Eqn. (4) purports to evaluate the voltage across the circuit-breaker, but it appears to neglect the fact that there is an inductive circuit on each side of the circuit-breaker.

Fig. 11, curve (*d*), shows the theoretical limit of over-voltage allowing for circuit-breaker effect.

With the advent of higher-voltage systems the trend must surely be for circuit-breakers of high voltage level, or will the B.E.A. guarantee the 275 kV system not to reach 300 kV or more? It may well be then that this curve (*d*) is an optimistic outlook. Further, if repeated gap breakdown occurs, secondary oscillations of considerable magnitude can be experienced, and in that respect there is some virtue in shunting by non-linear resistors.

In discussing switching surges I suggest that it is not only the circuit-breaker which chops the current that produces over-voltages. A circuit-breaker which tends to draw long arcs on switching magnetizing current also tends to give restrike at comparatively high voltages, and such strikes can produce some undesirable conditions on transformer windings. They can represent the application of a "near unit function" voltage wave.

Fig. 27 is of great interest in emphasizing the fact that oil circuit-breakers do chop. From my remarks it must be evident that I do not support the author's conclusions without considerable modification.

Mr. H. W. Hardern (*at Manchester*): I am reminded by Fig. 25 of difficulties we experienced some years ago with a 15 MVA 132 kV shunt reactor. As this was at first installed, the neutral point was insulated, and frequent terminal flashovers were experienced on switching out by oil circuit-breakers. Later the

neutral point was brought out of the tank and solidly earthed, after which there were no further flashovers. This experience is in accordance with lines 3 and 4 of Fig. 25.

In his final Conclusion the author rightly says that the voltage produced in current chopping depends on the characteristics of the switch and of the reactor or transformer. It is apparent from the fundamental equations that to effect an improvement it is required to reduce the inductance of the reactor or transformer and increase the effective capacitance. Let us see what can be done in this direction. In the case of a shunt reactor, it is inductance that is required, so this cannot be reduced. With a transformer, the main inductance present is the magnetizing reactance of the core, dependent on the size of the transformer and the steel characteristics. It will be much the same for any make of transformer, and it is largely outside the control of the designer. However, the use of a bridging reactor for on-load tap changers can considerably increase the voltages produced on current chopping, and is therefore to be avoided from this point of view. This is a further argument in favour of reactor transition for on-load tap changers.

As regards the other parameter, the effective capacitance of the winding, I should like to sound a note of caution regarding the values shown in Fig. 29. Whilst these may be taken as indicating the order of magnitude, quite wide variations from them must be expected depending on such requirements in the transformer as reactance, tapping range and transport dimensions. However—and I should like the author's confirmation on this point—it appears from examination of Section 8 that the capacitance of the transformer *per se* is liable to be swamped by other capacitances present, whether under experimental testing conditions or the actual operating conditions. Is this correct?

Mr. R. W. Blower (*at Manchester*): I would differ from the author in his assessment of the importance of current chopping over-voltages, which he sets out in the Introduction.

In my opinion the greater interest in current-chopping voltages with higher-voltage systems is not due to any special danger to insulation arising here. Most of these systems are equipped with devices such as surge diverters, rod-gaps, etc., for protection from atmospheric surges, and it is this protection, which has to operate at voltages intermediate between the system voltage and the insulation level of the gear, which has to be considered. The problem is therefore not so much the effect of chopping over-voltages on insulation but the behaviour of the over-voltage protection.

Experience seems to show that the over-voltage protection is frequently, though not invariably, quite capable of taking care of the switching over-voltage. For example, if surge diverters were used they would limit and break any power follow-current. The question then would be the suitability of the non-linear resistors incorporated in the surge diverters for taking up the energy discharged. Settling this point should present no more difficulty than settling the size of the non-linear resistors, if they were used, for voltage limitation, in parallel with the circuit-breaker gap. In surge diverters the non-linear resistors would, however, be more generally useful.

With reference to Section 2.1, I do not think that Fig. 1 is representative of all air circuit-breakers, since one metal-splitter-plate design does not exhibit a post-arc current at all approaching the values shown and the arc time-constant with it is much lower. I am unable to follow how the last equation in Section 13.3 has been used to calculate the curves of Fig. 1(*b*). I thought at first that the measured voltage/time curves might have been taken as given, but that does not seem quite to line up with the curves shown. Could this be explained further, and would the author state which starting conditions and which values of arc constant he has used, and also whether the latter were derived from independent measurements. Have the applied voltage and the constants of the external circuit been taken into account, and in what manner?

Fig. 23 purports to show the relation between the ratio of the gap strength at the moment of the restriking peak and at the moment of the suppression peak. The time interval between these peaks becomes smaller with increasing frequency, and I should have expected γ to approach 1 for higher frequencies. Is this correct?

Mr. W. H. Thompson (*at Manchester*): The author refers to arc interruption as being basically a thermal effect. Physicists have long been telling us that the electric arc is the rapid passage of electrons in one direction across the gap and the slower movement of the heavier ions in the opposite direction, and that the collisions which occur from these contrary movements produce the heat and temperature of the arc and put an amount of system energy in thermal storage. They also tell us that the current in the arc at any moment is a measure of the electron density in the arc core. If this is so, two things must follow, i.e. near the zero pause the electron density must diminish and the velocity become less, and even cease, because in the next half-cycle it will be in the opposite direction. During this period the recombination of ions and electrons takes place. I think current chopping is no more than a sudden and rapid increase in this process of recombination, accelerated by the circuit-breaker interrupting device.

If a sudden blast of high-pressure cold air is directed upon the arc, not only will the side-band cloud of ionized matter and molten copper be blown away, but also near zero pause when conditions are propitious, the air molecules will entangle themselves in the arc core and so hasten recombination to an extent that might force current zero before the natural time and so produce chopping.

The E.R.A. issued a report containing an equation relating minimum air pressure for interruption in an air-blast circuit-breaker with shunt capacitance, shunt arc resistance and inductance. The author's views on shunt capacitance agree with this, as shown in the relation between the two curves in Fig. 7. He also agrees on the shunt arc-resistance effect, but does not think this has much practical use because of the disproportionate values involved, i.e. 2 000 ohms for the resistance and 15 500 ohms for transformer reactance. The maximum rate of change of flux density caused by the return of $\frac{1}{2}LI^2$ energy to the circuit occurs across the magnetic zero. The effect is the same as that shown by the two peaks in the lower curves of Fig. 12. Therefore, if on chopping, the collapse of current can be prevented from reaching zero, the worst restriking peak will be avoided. It is here that a non-linear shunting resistor is of particular value in acting as a damper on the h.f. oscillations.

The effect of inductance is obvious in that the voltage must be equal to the current chopped times the transformer surge impedance: i.e. $V = I\sqrt{(L/C)}$, so that the lower the inductance, the lower the voltage becomes.

The curves in Fig. 7 and values in Table 1 can be misleading regarding the effect of r.m.s. current on current chopped. It will be agreed that r.m.s. current represents a store of energy which must be reduced to a certain critical value for a given circuit-breaker before chopping is possible. Therefore, the more energy released into the arc by the loop of r.m.s. current, the longer will it take a given circuit-breaker to reduce that energy to the critical chopping value. Fig. 7 and Table 1 may be correct for the values used, but are misleading by implication for currents of thousands of amperes. I suggest the curve relating r.m.s. current with current chopped will be, for a given circuit-breaker, slowly rising to the maximum current chop possible for that circuit-breaker and then rapidly falling until a

value of r.m.s. current is reached beyond which that circuit-breaker is incapable of chopping.

Mr. W. A. McNeill (*at Manchester*): In the dark ages of electrical engineering it was the very comforting practice to blame most insulation failures on over-voltage transients of mysterious origin and unknown magnitude. This practice was particularly comforting because everyone was equally in the dark and there was never any evidence to disprove the theory.

Then a very serious turn of events occurred—serious from the point of view of a switchgear designer; someone had the temerity to suggest that it might be the circuit-breaker itself that was creating the over-voltage. The advent of the air-blast circuit-breaker produced the fertile ground in which such treasonable thoughts were nurtured.

The upshot, however, was that switchgear designers gave serious consideration to the conditions favouring the creation of switching transients, and many tests were carried out at the various short-circuit testing stations. It was soon demonstrated that the interrupting device alone was not the culprit, and that the question of whether serious over-voltages were produced depended equally on the nature of the circuit in which the circuit-breaker was connected. It was also shown that the requirements of a circuit-breaker to limit transient over-voltages were not necessarily the same for inductive and capacitive currents.

There have been a number of Institution papers during the last ten years which have referred to this subject, but none has been primarily devoted to switching transients. This paper is therefore welcome evidence of the work that has been done at one research establishment. I am disappointed, however, that it has been limited only to current chopping. I do not believe that this subject can be dissociated from the kindred problem of capacitance switching. I feel, therefore, that the conclusions reached by the author have a much more limited value than would have been the case if both phenomena had been included.

I also feel that the paper does not deal adequately with the basic difference between air-blast and oil circuit-breakers—each has its particular virtues, but from a consideration of Fig. 27, the impression could be gained that there is no practical difference between them when interrupting small inductive currents. This impression is contradicted in conclusion (j), which rightly points out that chopping voltages tend to be lower with the oil circuit-breaker because of the small gap at which clearance can take place. But equally important is the fact that the gap can rapidly increase to a size adequate to prevent restrikes when clearing capacitance currents. It is therefore self-compensating, whereas the air-blast circuit-breaker with its fixed gap is not.

Mr. F. W. Gee (*at Manchester*): In Section 8, where the effect of a tap-change reactor is investigated, it is shown that a mid-point reactor may increase the transient voltage owing to current chopping. This is due to the increase in the transformer magnetizing current when the reactor is in a bridging position (reactor "in," Table 3). When the reactor is in the series position it does not add to the magnetizing current, and has therefore no effect on the transient voltages.

If, however, the bridging position is used only during transition between tappings, the probability of current chopping coinciding with this transition period is so small that the added risk is negligible.

With some designs of tap-changing gear the bridging position is, in fact, used only for transition, so that it is then wrong to infer that resistor transition is preferable to reactor transition.

When the running positions of the tap-changing gear avoid the use of the reactor in the bridging position, the conditions during any current chopping which is liable to occur will be no worse than with gear using resistors.

Mr. H. L. Thomas (*at Manchester*): The phenomenon of repetitive current chopping and restriking is equivalent to the application of a steep-fronted impulse voltage at each restrike, and if the repetition frequency should be such as to excite resonance or even partial resonance with any of the natural frequencies of a transformer or reactor winding, dangerous voltages might easily be set up. The natural frequencies of parts of a transformer winding such as between turns or coils, or tappings, may possibly range from megacycles down to kilocycles. I should like to ask the author whether he can quote any figures for the range of repetition frequencies likely to be encountered due to circuit-breaker operation.

Mr. W. L. Kidd (*at Glasgow*): The records of arc resistance in Figs. 3, 4 and 5 show significant differences in the arc-resistance characteristics, and I should like to know whether the author can explain the marked tendency for oscillation in the resistance curve of Fig. 4.

The formulae in Section 3.5.1 appear to be a very simple interpretation of the circuit conditions during transformer switching as they ignore the conditions on the supply side of the circuit-breaker and also do not include any terms representing current and voltage decrement. Is it possible to ignore the supply-side capacitance and inductance in practice, when estimating the voltage rise due to current chopping?

The capacitance C_T is always referred to by the author as the transformer self-capacitance. I suggest that in practice where there is a length of cable between the circuit-breaker and transformer, the cable capacitance should be added to the transformer self-capacitance and will materially reduce the value of e_T and e_B, and also the rate of rise of e_T. A 30 yd length of 33 kV cable might increase the capacitance C_T from $0{\cdot}003\,\mu$F to $0{\cdot}012\,\mu$F and therefore halve e_T.

In Section 3.3 it is shown that an increase in the effective capacitance in parallel with the circuit-breaker increases the maximum current that can be chopped. Does this refer to capacitors connected direct across the circuit-breaker gap to control the voltage distribution when there are several breaks in series, or does it apply to cable connections on each side of the circuit-breaker? Records of performance of some circuit-breakers which use capacitors for controlling the voltage distribution across the circuit-breaker gap show that these circuit-breakers can be used for switching unloaded transformers or overhead lines without producing any dangerous over-voltages.

Air-break isolators are frequently used for breaking transformer magnetizing current. This usually results in a long arc being drawn, but so far as I am aware it does not give rise to any abnormal voltages on the system. The characteristics of the arc are very different from either those of the air-blast or oil circuit-breaker described in the paper, and I wonder whether the author has made any tests with air-break isolators.

The author shows in Section 7 that resistance shunts across the circuit-breaker gap have no material effect on over-voltages produced by current chopping, but tests on some designs of air-blast circuit-breaker with non-linear resistors show that the performance of the circuit-breaker is materially improved by the non-linear resistors—the voltage due to current chopping being reduced 50–60%.

The author recently carried out switch tests on an unloaded 33 kV feeder and transformer on our system to determine what over-voltages might be expected. The results were very satisfactory and showed that, provided the system neutral is earthed, no dangerous over-voltages need be expected. The tests did, however, confirm that switching long unloaded 33 kV feeders can produce severe voltage conditions in the arc-control device.

Mr. L. L. Alston (*at Glasgow*): I should like to ask the author whether non-linear units were included in the voltage divider

sed to record arc voltage. The voltage across the test-gap creases considerably when the arc deionizes, as indicated by igs. 3, 4, 5 and 20. If the voltage-divider ratio is such that a latively large voltage appears at the cathode-ray oscillograph hile the arc is burning, a non-linear unit may be necessary to otect the instrument when the arc deionizes.

Were photographs taken to study the movement of the arc, nd if so, could the author give details of the method employed?

I was particularly interested in the author's remarks on power llow-on current (Section 8). Did he investigate experimentally e effect of factors other than gap spacing on the likelihood of ower follow-on current flowing?

Mr. J. K. Wheeldon (*at Glasgow*): The author suggests in the troduction that the insulation levels for lower-voltage gear are higher multiple of the system voltage than for higher voltages, is being a consequence of the natural limit of the atmospheric ver-voltage approach. Surely many lower-voltage systems are ble systems and not prone to atmospheric disturbances, and e natural limit of atmospheric over-voltage is, after all, fairly gh. In my opinion, on current-chopping voltages with the gher-voltage system, emphasis should be placed on the extent which chopping over-voltages have to be kept below the perating level of the over-voltage protection, and on the extent which the over-voltage protection is capable of taking care of em. I believe in many circumstances the over-voltage protecon will be effective and a more economical answer to the oblem, although I agree that circuit layout and circuit-breaker sign should be given attention. It is of interest to read that, in e discussion on a paper on bushings, a statement was made that some of the larger circuit-breakers the cost of the bushings was % of the total cost of the circuit-breaker. In my opinion this is gh, but certainly for a 132 kV oil circuit-breaker for 2 500 MVA e insulation cost is 34% of the total, whereas for 33 kV and 0 MVA it is 36%.

In Section 2.1 the author discusses arc extinction in air-break rcuit-breakers. I should be interested to know whether the rcuit-breaker was of the metal-splitter-plate type which is mmon in this country. Since this employs a large number of ort arcs in series, the conditions at the arc roots are most portant, and one would not expect the behaviour of this type circuit-breaker to be quite the same as one using a single long c where conditions in the arc column will be decisive.

In Section 3.5.2, it is stated that the shunt resistance R_T, presenting eddy current loss, is independent of frequency. Is is correct? I thought the lamination of the core is usually apted to the power frequency, and that at higher frequencies perfect flux penetration will occur. This should result in an crease of the representative shunt resistance with the square of e frequency.

To conclude, I see the importance of current chopping overltage in a setting somewhat differing from that given in the troduction. I would rather differentiate between systems with d without devices for protection from atmospheric surges. stems without surge protection include many lower voltages, particular cable systems. Here current chopping over-voltage uld have to be related to the insulation level of the gear which, art from winding insulation, is for the most part sufficiently ll represented by power-frequency test voltages.

Mr. J. S. Cliff (*at Birmingham*): The author has given test data one transformer and two forms of circuit-breaker, the details the latter not being disclosed. Such information, while being aluable contribution, is not, by itself, sufficient as the basis general conclusions applicable to all voltages, ratings of nsformers and different types of circuit-breaker.

The Swiss have recently reported upon a more extensive series investigations covering 14 circuit-breakers of various types, and 9 transformers, with voltages from 6 to 220 kV. At the equivalent of 132 kV the Swiss values are higher than the author's, but he was handicapped by the limitation set by his 22 in and 7 in protective gaps.

Tests with voltage waveforms similar to switching over-voltages indicate that apparatus will only withstand a switching over-voltage of 90% of the 1/50 microsec insulation level. Using the lowest recommended insulation levels* we get the following comparison between the maximum permissible voltage ratio based on the insulation withstand voltage, and the maximum voltage ratios corresponding to the Swiss measurements:

Rating	I.E.C. insulation level	0·9 × insulation level	Maximum permissible voltage ratio	Maximum Swiss voltage ratio
kV	kV	kV		
11	75	67·5	7·5	7·0
33	170	153	5·7	—
66	325	290	5·3	6·05
132	550	495	4·6	4·6
275	1 050	945	4·2	4·5

This comparison shows that there is no margin throughout the voltage range. However, experience up to 132 kV—mainly with oil circuit-breakers—has indicated that there is little risk to insulation with protective gaps. As the voltage rating rises the margin gets less, so it is worth while to examine the problem at 275 kV.

If the over-voltage control is by the circuit-breaker arc-gap, the gap must not break down during faults involving loss of synchronism

$$\frac{275 \times 1\cdot 1 \times 1\cdot 414 \times 2 \times 1\cdot 8}{1\cdot 73} = 890\,\text{kV}$$

To give protection, however, breakdown must occur below 945 kV. This is too close for reliability, since Fig. 8 indicates that gap performance is not very consistent.

Special high-value switching resistors could be used, but these would complicate the circuit-breaker design. Separate over-voltage protection appears to be the best solution, preferably by non-linear surge diverters. British-made surge diverters are now available which have been shown by B.E.A. tests to be satisfactory for use even in the heavily polluted atmospheres which occur in this country, and 18 years' experience on a circuit-breaker testing plant, where frequent operation occurs owing to current chopping, has shown that they have ample capacity for dealing with the energy due to switching over-voltages.

Mr. H. M. Fricke (*at Birmingham*): With reference to the author's statement that the requirements of circuit-breaker makers needed somewhat different characteristics in transformers, I should like to know what alteration in design of transformers he would like to see and whether he would wish the capacitance figures of the windings to be modified in any way.

Mr. J. H. C. Peters (*at Birmingham*): I should like to support the author's remarks in regard to sharing out the blame for production of over-voltages since there is a tendency nowadays to put all the blame on the circuit-breaker, whereas the other plant connected to the system may also play its part in this matter.

I should also like to ask the author for more details regarding the type of oil circuit-breaker he mentions.

Dealing specifically with extra-high-voltage circuit-breakers, 110 kV and above, is he referring to small-oil-volume circuit-breakers or bulk-oil circuit-breakers? It may be that the result is roughly the same for both types, but I do happen to know that certain types of small-oil-volume circuit-breaker do, under

* I.E.C. Series I European values.

certain conditions, produce considerably higher over-voltages than those experienced with bulk-oil circuit-breakers or air-blast circuit-breakers. This might well be expected from the fact that, owing to the very small quantities of oil used, these circuit-breakers have to operate very rapidly in order to keep down the rise of pressure in the interrupter.

Mr. E. V. Hardaker (*at Birmingham*): In view of the satisfactory experience with the 132 kV circuit-breakers on the Grid system, and bearing in mind the transient over-voltage values published in the paper, I should have thought that the insulation level of 132 kV equipment was adequate without recourse to resistance switching or the provision of surge diverters. I shall be glad to know whether the author agrees with this point of view.

Mr. E. Bolton (*at Birmingham*): Several of the records shown by the author show quite high surge currents during current chopping. I wonder whether, during the course of the tests, any measurements of these surge currents were taken, recording their peak values, and whether anything unusually high was found, especially under transient conditions when the transformer was switched out immediately it had been switched on.

I do not know whether the author has any further comments to make on Fig. 8, which shows indirectly the rate of rise of recovery voltage for an air-blast circuit-breaker. There appears to be a very wide scatter—in the best case he gets 1 100 volts per microsec, as compared with 150 volts per microsec under the worst conditions. Is that typical of any air-blast circuit-breaker, or is it rather a special one?

Mr. J. A. Spence (*at Liverpool*): On the subject of arc extinction, I would ask the author whether the pressure of the gases in an arc has any significance in arc resistance. As the pressure and electric strength of gases are related, I would ask whether pressure is related to the arc resistance at the temperatures experienced in that arc.

I should also like the author to confirm whether the large masses of metal associated with the contacts of the air-blast circuit-breaker contribute to some extent to the extinction of an arc by cooling it, in the same way that an air-blast also cools the arc and extinguishes it rapidly.

Referring to Fig. 8, I assume that the variations indicated in this Figure are possibly due to a turbulence of the air-blast and to the variation in arc cooling due to this turbulence. If that is correct, would the smoothness or streamlining of the passage of the air have any effect on the performance of an air-blast circuit-breaker?

I think it would have been better if the scales on Figs. 15 and 16 had been made the same, since it would then have been easier to compare the air-blast circuit-breakers and oil circuit-breakers regarding this feature. I find it rather hard to reconcile Figs. 15 and 16 in that the shape of the curve for the air-blast circuit-breaker in Fig. 16 is quite different from that in Fig. 15.

Mr. A. J. Coveney (*at Liverpool*): It would appear that the question of current chopping has had to receive much greater attention with the advent of arc-control devices and air-blast switchgear designed in recent years to deal with the higher voltages, the higher speed of arc clearances required and the additional short-circuit values which switchgear designers had to meet.

Whilst the paper provides valuable data and formulae of a scientific and mathematical nature, it is well perhaps to look at the question from a practical point of view. The author agrees that the voltage surges resulting from current chopping are of values well below the normal insulation levels provided, and if these surges do not interfere with the normal operation of system protection, the question, I think, resolves itself into how long this current chopping can continue without damage.

The problem appears to be one of switchgear construction, in that the arc should be extinguished before the moving contact leaves the arc-control device, or in the case of air-blast switchgear, before the series switch commences to open.

If, therefore, the circuit-breakers are designed to perform satisfactorily within the limits specified by the appropriate British Standard, does the author consider that system capacity changes at some future date would make it possible for these circuit-breakers to fail on account of current chopping due to this new condition? There seems to be a need for a British Standard which will incorporate many of the data given by the author.

Dr. H. Edels (*at Liverpool*): The operating performance of circuit-breakers depends ultimately upon the physical phenomena occurring in the gap region during the arcing and post-arc periods. In this respect it would be of interest to determine the details of the processes occurring during a current chop, and hence to determine whether any significant difference exists between the recovery of the gap after current chopping and after a natural current zero. For example, the current oscillograms given in the paper are presumably restricted by instrumentation with respect to both time resolution and the lower limit of the current amplitude, but it would be interesting to know the rate of current decrease and whether currents of the order of 100 mA, and hence possibly glow discharges, exist for any appreciable period before conduction finally ceases. Data of this nature may well lead to a clearer understanding of the mechanism of current chopping, and may indicate differences in the processes occurring in various types of circuit-breaker.

I am interested in this problem because, in the Electrical Engineering Department of Liverpool University, we are carrying out a number of experiments associated with switchgear, and in particular, one investigation which is designed to measure the recovery of a gap after an arc has been artificially chopped. In this experiment a d.c. arc under conditions of free convective equilibrium is short-circuited, so that the current in the gap is reduced from approximately 50 amp to zero, in the order of 1 microsec. Simultaneously with the short-circuiting, the gap is isolated from the d.c. source. After a controlled delay time from current zero, the gap is subjected to an impulse voltage which approximates closely to a unit function (front 0·1 microsec, tail 50 microsec). By varying this voltage under given test conditions, it is possible to determine the re-ignition voltage of the gap for the given delay time, and further, by varying the delay time a complete re-ignition characteristic can be obtained. Such a characteristic would be similar to those given by Figs. [illegible] and 15 but would be more likely to yield to analysis since the gap is allowed to recover freely during the delay period before the impulse is applied, and also because the impulse voltage itself has a simple analytic form.

Finally, I should like to refer to Section 13.3 in which the electrical conductivity of the arc is taken to be approximately proportional to T^{14}. If we can assume normal arc properties, then use of the Saha and mobility equations leads to a formula for the electrical conductivity given by a constant times $\left[T^{3/4}\exp\left(-\frac{\text{constant}}{T}\right)\right]$. It is true that the Saha equation assumes thermodynamic equilibrium, which may well not exist during the current-zero period, and that other disturbing factors may be influencing the conductivity. In these circumstances it would be useful if the author could indicate the derivation of the conductivity proportionality (T^{14}) given in the paper.

Mr. M. A. Bird (*at Liverpool*): To many people the terms "current chopping" and "magnetizing" current are inseparable. I think it should be mentioned that current chopping can occur with all small currents. The phenomenon is important only fo

nagnetizing currents; for capacitance currents it is usually eneficial.

Circuit-breakers, especially those for the highest voltages, hould not and need not produce severe over-voltages. The uthor describes how restriking of the gaps in an air-blast ircuit-breaker can limit the over-voltages produced; he also tresses the random nature of the phenomena of magnetizing-urrent interruption. In some designs of air-blast circuit-reaker, maximum air pressure and maximum contact separation an occur approximately one half-cycle after contact separation; uch circuit-breakers can limit the chopping voltages only if inal clearance of the current takes place within approximately ne quarter-cycle after contact separation, and this is what iormally happens. It seems to me, however, that it is almost mpossible to prove that service conditions cannot occur which vill produce serious over-voltages, even if shunt reactors are gnored.

Non-linear resistance shunts of high ohmic resistance can ositively prevent the generation of such over-voltages; for xample, a potential chopping voltage of 1 300 kV peak on a 75 kV transformer would be limited to approximately 500 kV peak.

The author states that periodic sudden drops in arc resistance ould account completely for the current oscillations observed. Can he say what causes these sudden drops in arc resistance?

With reference to Fig. 7, test experience on actual systems hows that curve (*a*) is more realistic than curve (*b*); in other vords, the parallel capacitance has to be increased very con-iderably in order to chop currents exceeding 12 amp.

Were the tests on which Fig. 21 is based carried out on one eactor with varying current, or on a variety of reactors?

In the paper and in introductory remarks the author has ointed out that, although oil and air-blast circuit-breakers chop urrents of similar magnitude, and in so doing produce similar oltages, the air-blast circuit-breaker produces a few relatively evere chops and the oil circuit-breaker a multiplicity of relatively ninor chops. Certain types of air-blast circuit-breakers, iowever, behave in a manner resembling that attributed by the uthor to the oil circuit-breakers. Is there any explanation of hese differences in behaviour?

Mr. J. E. Macfarlane (*at Liverpool*): Like Mr. Spence I am omewhat dubious in accepting what the author said about he incidence of lightning, although with the system voltages ncreasing it is not so likely to cause so many outages.

There are a number of shunt reactors in south-east England on he 66 kV cable network; are any results available to confirm he author's figures? Will shunt reactors be used with the 75 kV overhead lines?

Can the author say whether it makes any difference to the esults if the transformer is non-resonating or of the screened ype compared with those tested?

Although we have no high-voltage direct current in this ountry, manufacturers are looking for new export orders, and igh-voltage d.c. transmission is in being. Some of the author's vork may be applicable to high-voltage d.c. circuit-breakers.

Prof. G. W. Carter (*at Barnsley*): The possibility that dangerous oltages may arise from current chopping is not to be denied, ut the data in the paper are in some respects too vague to help s in assessing the risk of such voltages. For example, in Fig. 11 he voltage scale is undefined; in Fig. 14 we are given insufficient nformation about the circuit to enable us to judge whether the oltage indicated is excessive, and the curves are based upon a mall number of tests, so that they give no assurance about the vorst that can happen in a large number of operations.

The discussion of the two mechanisms of current chopping in ection 3 is illuminating, but if Fig. 2 represents the thermal nechanism accurately, the resulting chopping is very mild. As one aspect of the thermal mechanism is successfully dealt with by a theoretical method in Section 13.3, would it not be possible for the maximum current that can be chopped to be predicted by applying the same theory?

Fig. 24 shows that voltage produced by current chopping may be periodic with an almost uniform frequency. If this frequency happens to coincide with a natural frequency of the connected apparatus, is it possible for the danger from current chopping to be enhanced by resonance?

Mr. A. F. B. Young (*in reply*): Mr. Ehrenberg and Mr. Kidd have referred to the omission of reference to the effect of the voltage transient on the supply side of the circuit-breaker as a result of current-chopping. This transient has no direct effect upon the voltage across the transformer being switched, but does have some effect upon the voltage across the circuit-breaker. This effect is usually quite small since the amplitude of the transient is much smaller than that across the transformer and is rapidly damped, and also the frequency is very much higher. The main effect is therefore to give a double-frequency waveform to the transient voltage across the circuit-breaker, but its peak value is usually substantially as given by eqn. (4).

The possibility of exciting resonance in a transformer winding as a result of current-chopping has been mentioned by Mr. Hore, Mr. Thomas and Prof. Carter. When chopping occurs high frequencies are often present in the transient voltage generated across the transformer being switched, but their amplitude is only a very small fraction of the total amplitude and they are rapidly damped. Some amplification of these high-frequency components could occur as a result of multiple current-chopping and restriking of the circuit-breaker contact-gap, but the frequency of the restriking has to be very high. Since the amplitude of the restrikes is roughly inversely proportional to frequency, the exciting voltage is very small in practice and dangerous resonance voltages are most unlikely to be produced.

Mention has been made by Mr. Kidd and Mr. Bird of the use of non-linear resistors to reduce transient voltages due to switching. Their fitting introduces additional components with complications and hazards and with new problems, notably the need for means of interrupting the current of the resistor in series with the load after the main break has cleared, and also the complex problem of the design of a resistor suitable for the full range of duties which a circuit-breaker must perform.

As mentioned by Messrs. Cliffe, Blower and Bruce, surge diverters and rod-gaps set sufficiently low can limit transient voltages produced by switching inductive loads. Most surge diverters will be adequate for this duty. If a rod-gap flashes over the transformer energy will be dissipated in the arc very rapidly and without damage. If the circuit-breaker contact-gap were to restrike immediately after the gap flashover the duty could be severe for an oil circuit-breaker, but the likelihood of this occurring is very remote.

Messrs. Hore, Cliffe and Bolton doubt the effectiveness of the circuit-breaker gap as a means of limiting transient voltages in view of the variability of gap breakdown strength shown in Fig. 8. The spread of results in this diagram is somewhat increased by the fact that some points were taken when the contacts were not fully open. Nevertheless there is a fairly large spread, and this results in the transient voltage being limited to a value below the maximum possible, or possibly to a slightly increased arc duration, a point of little importance at these low currents.

In the same connection it has been pointed out that the circuit-breaker contact-gap must be arranged to withstand the large restriking voltage transients associated with fault switching without restriking. The two requirements of limiting transient voltages due to switching inductive currents adequately and also

withstanding restriking-voltage transients are not irreconcilable, since current-chopping begins immediately after contact separation when the gap strength can be kept low, and the gap strength can then be allowed to rise so that faults can be cleared one to two loops later.

Turning now to some of the points raised by individual speakers, Mr. Hore uses the data of Table 2 to show that random effects do not reduce transient voltage. It must be appreciated, however, that the data of Table 2 is a selection of the highest transient voltages obtained for a series of different conditions. The lower figures, which were not presented, were lower by virtue of random effects.

Mr. Ehrenberg seems to interpret the paper as championing the thermal theory of arc extinction. This is not intended and mention has been made of it only as one process involved. Circuit-breakers probably do not chop at currents of several thousand amperes, but this is a point which is difficult to prove, since, as the current increases, the transient voltage produced by chopping becomes smaller and is insignificant under short-circuit conditions. Space does not permit giving full details of measuring techniques, but the following brief details may be of interest. The low currents were measured with a specially made shunt, and voltages with capacitor-resistor dividers, and both were recorded by a high-speed cathode-ray oscillograph. Arc resistances were deduced from the two measurements.

Messrs. Hardern and Gee very properly draw attention to the type of reactance tap-changing equipment which connects the reactor in circuit only during transition, and therefore has no effect on transient voltages due to current-chopping.

The arc-resistance fluctuations referred to by Mr. Kidd may well be due to the arc being repeatedly increased in length and part of the increased length being short-circuited.

Mr. Wheeldon is quite correct in saying that at high frequencies the core-loss resistance will be greater than the power-frequency value, but in current-chopping the frequency of the transient is usually quite low and of the order of 300 c/s for transformers so that the 50 c/s figure is not far wrong.

Mr. Cliffe refers to the data published in Switzerland. These figures are most valuable for determining maximum permissible transient figures, but no mention was made of them, since the purpose of the paper was to investigate the mechanism of current-chopping and its effects rather than to recommend maximum permissible switching voltages.

Mr. Spence finds Figs. 15 and 16 hard to reconcile. This difficulty may be resolved if it is realized that Fig. 15 shows how the gap electric strength recovers if the current is cut off after three loops of arcing, while Fig. 16 shows the envelope of a large series of such curves for different arc durations.

Mr. Bird refers to a type of air-blast circuit-breaker which gives multiple current-chopping. This would be explained if the speed of break of the contacts were small, perhaps at the beginning of the opening operation.

DIGESTS OF INSTITUTION MONOGRAPHS

MATRIX METHODS FOR THE EVALUATION OF SIMULTANEOUS FAULTS IN THREE-PHASE SYSTEMS

621.3.014.7 Monograph No. 125 S

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(DIGEST *of a paper published in April,* 1955, *as an* INSTITUTION MONOGRAPH *and republished in September,* 1955, *in Part C of the* PROCEEDINGS.)

The growing availability of automatic digital computers, together with the large number of standard programmes worked out and covering a wide range of mathematical problems, has made the analysis of electrical networks in terms of the circuit equations a feasible proposition. The equations are usually written in terms of the mesh currents and also in matrix form, i.e. the impedance coefficients are written separately from the mesh currents and form the so-called impedance matrix of the network. The matrix form is the best method of presenting the problem to a computer for solution. Stigant's rule,[2] enables the impedance matrix of a network to be written down by inspection.

The analysis of a power system with unbalanced faults or loads is difficult if carried out in terms of the line currents because of the presence of a large number of cross-overs and also because the mutual inductances between the phases of a 3-phase machine are not bilateral. These difficulties can be overcome by using the symmetrical components of Fortescue, but unless the faults are balanced with respect to phase *a* the symmetrical-component circuit representing the network may be very complicated and contain a number of phase-shifting transformers. The paper illustrates the application of Stigant's rule to such networks.

However, unless the system being analysed is very small, its symmetrical-component equivalent circuit may well be too complex to deduce. The paper shows how the voltage and impedance matrices for such a complex network may be deduced from those of a simpler (though related) network when a circuit diagram of the complex network is not available. In this method all faults are first replaced by a balanced condition; for example a single-line short-circuit to ground is replaced by a 3-phase short-circuit to ground. If this balanced system is now represented in terms of symmetrical components we obtain three entirely separate networks for the zero, positive and negative sequences respectively. These three sub-networks are the starting-point of the analysis and form the "primitive network." The voltage and impedance matrices for this network are easily written down once the mesh currents have been decided on. The choice of the mesh currents is governed by the requirements of the problem, but in general it is best if only one current flows through a fault path.

Because of the unsymmetrical nature of the faults, relationships

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r constraints exist between some of the symmetrical-component nesh currents; for example, for a single line to ground fault on line we have $I_0 = I_1 = I_2$. Thus the analysis may proceed in terms of ewer currents than originally used in the primitive network. These ew currents are now chosen and a constraint matrix is set up vhich gives the currents in the primitive network in terms of the ew currents. The engineer's task finishes here, for the voltage nd impedance matrices in terms of the new currents are obtained y a manipulation of the constraint matrix with the voltage and mpedance matrices of the primitive network using formulae eveloped by Kron,[3] and finally the currents are evaluated. All nis work may be done on a computer.

The paper illustrates the application of the technique to a wide ariety of fault conditions, including the treatment of fault mpedance.

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A NOTE ON THE SURFACE LOSS IN A LAMINATED POLE-FACE

621.313.044.6: 621.3.017.31 Monograph No. 123

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(Digest *of a paper published in March,* 1955, *as an* Institution Monograph *and republished in September*, 1955, *in Part C of the* Proceedings.)

The slotting of a machine armature introduces a ripple into the ir-gap flux. As the machine rotates, this ripple travels across the ole-faces, inducing eddy currents in them and thereby bringing nto existence a loss known as the surface loss. The calculation f this loss by classical electromagnetic methods was the subject f a paper by the author's father, the late Dr. F. W. Carter, who onsidered two cases, the solid pole-shoe and the pole-shoe ivided into very thin laminations; for the latter type, the loss er unit area was found to be proportional to the square of the amination thickness. More recent writers, believing that the ole-shoe laminations used in practice are too thick for Carter's aminated-shoe formula to be applicable, have derived approxinate formulae in which the loss is proportional to the first power f the lamination thickness; there is a certain amount of experinental support for such a law.

In the present paper the surface loss is calculated by classical heory without making any assumption as to the thickness of the aminations. The resulting formula contains too many indeendent variables to permit of general graphical representation; clearer view is obtained by discussing a particular case. Fig. 1 hows how the stator surface loss would vary with lamination hickness in a 4-pole 50c/s induction motor having 43 rotor slots, e rotor slot pitch being 0·874cm and the stator iron having a esistivity of 35 × 10^{-8}ohm-m. The uncertainty as to the ffective permeability of the iron has been overcome by assuming hree values. The full curves show the loss values calculated om the author's formula; F. W. Carter's two approximations e also plotted, and so is a more recent formula which makes e loss vary as the lamination thickness. It will be seen that . W. Carter's formulae approximate closely to two regions of e curves, but that the approximation afforded by the other rmula is not good. Furthermore, F. W. Carter's laminatedole formula is seen to apply, not to the thinnest laminations, but

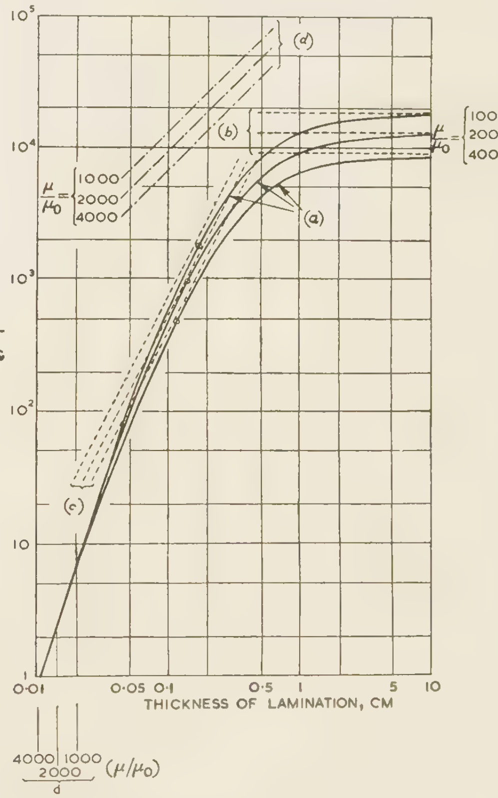

Fig. 1.—Application of the theory to the experimental machine.

(*a*) Author's formula.
(*b*) F. W. Carter's solid-pole formula.
(*c*) F. W. Carter's laminated-pole formula.
(*d*) Gibbs's formula.

The ringed points indicate centres of validity zones for F. W. Carter's formula.
The wavelength of the inducing flux-ripple corresponds to a lamination thickness of 0·874cm.

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to an intermediate range. A simple criterion is given for determining whether F. W. Carter's laminated-pole formula is likely to be valid in any specific case; when applied to a particular design of alternator having mild-steel poles, this criterion shows that Carter's formula is likely to be valid for lamination thicknesses around 0·22 cm. This lies in the middle of the range of thicknesses commonly used for pole laminations, and shows that the assumption that Carter's formula applies only to very thin laminations is unjustified. Experimental results which point to a contrary conclusion are probably to be explained by the limitations of linear electromagnetic theory when applied to problems involving iron.

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THE INITIATION MECHANISM OF LONG SPARKS IN POINT-PLANE GAPS

621.3.015.54: 621.3.015.532 Monograph No. 124 M

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The mechanism of the growth of lightning discharges has been investigated by Schonland and his colleagues,[2–5] using mechanical-scanning camera techniques, and it has been shown that the lightning stroke is preceded by a streamer type of process known as the leader stroke. Allibone and Meek[6] have shown that similar phenomena are obtained for long sparks between a positive point and an earthed plane subjected to an impulse voltage in the laboratory.

The object of the present experiments has been to extend the results of earlier investigations by the use of improved techniques. The movement of the leader stroke across the gap was studied by means of a photo-multiplier, the output of which was recorded, after amplification, on a cathode-ray oscillograph. Measurements on leader strokes for different gap lengths and for different series resistors show that the leader stroke moves across the gap in a regular manner. For a given series resistor, it is found that the shapes of the distance/time curves for different gap lengths are similar, and that, if these curves are replotted as percentage-distance/percentage-time curves, they are identical to within the experimental error. Reduction of the series resistor causes the leader stroke to cross the gap more rapidly.

The use of a negative-plane/earthy-point arrangement of the circuit makes it possible to record the current flow in the circuit while the leader stroke is crossing the gap, and current/time curves for different gap lengths and series resistors are given. By combining these curves with the distance/time curves for the same gap lengths and series resistors, a relationship between the distance moved by the leader stroke and the charge flow in the circuit has been established. It is found that this relationship is a linear one, corresponding to a dissipation of approximately $0{\cdot}9\,\mu C$ of charge for every centimetre of movement of the leader stroke.

The behaviour of the leader stroke for gas pressures less than atmospheric has also been studied, and distance/time and current/time curves are presented.

The high sensitivity of the photo-multiplier system has enabled the distribution of light intensity in the head of the leader stroke to be investigated. It is found that the light emission falls of rapidly with distance from the centre of the hemispherical volum comprising the head of the leader stroke, but can still be detecte at a distance of 10 cm from the centre.

A similar light intensity distribution is found for the corona pulse which forms round the point at voltages insufficient to allow a leader stroke to be propagated. The peak light emission and peak current due to the corona pulse are shown plotted a functions of the applied voltage. The duration of the corona pulse is shown to vary inversely as the gas pressure.

The characteristics of the corona and leader stroke in nitrogen hydrogen and oxygen are investigated and it is shown that:

(*a*) The corona pulses in nitrogen and in hydrogen are of lon duration.
(*b*) A leader stroke mechanism is detected in nitrogen but i moves in such an apparently random manner that n curves are obtained.
(*c*) No evidence of a leader stroke is found in hydrogen.
(*d*) The corona pulse in oxygen is of very short duration.
(*e*) No evidence of a leader stroke in oxygen is found.

The durations of the corona pulses in nitrogen and hydroge (probable oxygen contamination, 0·4%) and oxygen support the view that the corona pulse duration is governed by the amoun of oxygen present.

It is concluded that:

(i) As yet no explanation exists for the production of ligh emission at a distance of 10 cm from the pointed elec trode in the corona pulse or at a similar distance from the highly luminous centre of the head of the leade stroke.
(ii) The motion of the leader stroke in the experiment described has been controlled almost entirely by the circuit constants.
(iii) The plane electrode (the cathode) plays no part in the discharge mechanism, other than the obvious role o the production of the required field, which suggests tha the processes involved in the propagation of the leade stroke are gas processes and not cathode processes.

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The paper is based partly on E.R.A. Reports Ref. L/T183 and L/T188.

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SECOND-ORDER TORQUE COMPONENTS IN THE SCHRAGE MOTOR OPERATING AT SYNCHRONOUS SPEED

621.313.333:621.3.016 Monograph No. 133 U

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It is well known that at an average speed nearing synchronism the Schrage motor is capable of showing periodic variations in speed and in primary current. These variations are accompanied by similar variations in torque, and the frequencies involved are functions of the slip.

The whole phenomenon can be appreciated by investigating the torque characteristics possessed by the machine operating at synchronous speed. This speed is chosen because then the generally rotating air-gap flux becomes stationary in space and can be compared with the flux in a d.c. machine. The slip being zero, the speed and primary current variations disappear, but if the torque is considered as a function of the air-gap flux-axis in space, then a torque variation may be measured.

If the total torque developed at synchronous speed is independent of the flux-axis position, the machine shows no hunting tendencies at other speeds and operation at synchronous speed is purely asynchronous. If, on the other hand, the torque varies with flux-axis position, the machine is capable of hunting and of operating synchronously at synchronous speed over a limited torque range.

The way in which the torque varies with flux-axis position depends on (*a*) asymmetry in the secondary circuits due to errors in brush positioning and/or unequal secondary resistances, and (*b*) the presence of space harmonics in the air-gap flux distribution. These effects can be taken into account in the following manner.

Neglecting all flux harmonics which at synchronous speed are rotating, let that part of the total flux which is stationary at this speed be

$$B = (B_1 \cos\theta - B_3 \cos 3\theta + B_5 \cos 5\theta - \dots) = \sum_{n \, 1}^{\infty} (-1)^{(n-1)/2} B_n \cos n\theta \quad . \quad (1)$$

where n is a positive odd integer, θ is in electrical radians, and B_n is the maximum flux density of the nth space harmonic.

Fig. 1 shows the components of the nth secondary phase of a U-phase (secondary) machine. To avoid complicated mathe-

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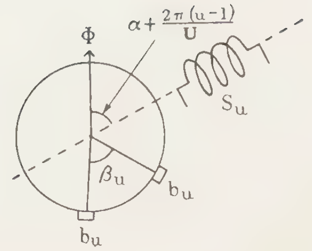

Fig. 1.—Components of the uth secondary phase with zero brush shift.

matics, it is assumed that the magnetic axes of the brush circuit and the stator winding are coincident (i.e. zero brush-shift) and that the only possible error in brush positioning is that of brush-spread. The combined axis of the uth secondary phase is at an angle $[\alpha + 2\pi(u - 1)/U]$ to the flux axis, α being the corresponding angle for secondary phase 1.

It can be shown that the direct voltage produced at the brushes of the uth phase due to rotation in the mth harmonic flux, $(-1)^{(m-1)/2}B_m \cos m\theta$, is given by

$$V_{um} = 2K_v k_m \sin \tfrac{1}{2}\beta_u \sin m[\alpha + 2\pi(u - 1)/U] \quad . \quad (2)$$

where K_v is a constant, k_m is the ratio of the mth space harmonic of voltage to the fundamental and β_u is the brush-spread angle.

If R_v is the total resistance round the secondary circuit (including effective resistance of brush contacts), the current flowing in this circuit at synchronous speed is

$$i_{um} = K_v(\beta_u/R_u)k_m \sin m[\alpha + 2\pi(u - 1)/U] \quad . \quad (3)$$

where $\frac{1}{2}\beta_u$ replaces $\sin \frac{1}{2}\beta_u$, since for normal synchronous operation the brush spreads are small.

The torque obtained when this current reacts with, say, the nth harmonic flux, $(-1)^{(n-1)/2}B_n \cos n\theta$, is given by

$$T_{umn} = 2i_{um}K_t\bar{\sigma}_n k_n \sin n[\alpha + 2\pi(u - 1)/U] \quad . \quad . \quad (4)$$

where K_t is constant and $\bar{\sigma}_n$ is a factor depending on the fundamental and nth harmonic winding factors of commutator and stator windings.

Combining eqns. (3) and (4) and making the appropriate summations, the total torque is given by

$$T = K_v K_t \sum_{u=1}^{\infty} (\beta_u/R_u) \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \bar{\sigma}_n k_n k_m \Big\{\cos (n - m)[\alpha + 2\pi(u - 1)/U] - \cos (n + m)[\alpha + 2\pi(u - 1)/U]\Big\} \quad . \quad (5)$$

This expression can be written in the form

$$T = K_v K_t[(f_0 A_0 + f_2 A_2 \cos 2\alpha + f_4 A_4 \cos 4\alpha + \ldots) - (g_2 A_2 \sin 2\alpha + g_4 A_4 \sin 4\alpha + \ldots)] \quad . \quad (6)$$

where the various coefficients are defined by the following equations:

$$f_a = \sum_{u=1}^{U} (\beta_u/R_u) \cos [2\alpha\pi(u - 1/U];$$

$$g_a = \sum_{u=1}^{U} (\beta_u/R_u) \sin [2\alpha\pi(u - 1)/U]$$

$$A_0 = 1;\ A_2 = (1 + \bar{\sigma}_3)k_3 - 1;$$

$$A_{a>z} = [1 + \bar{\sigma}_{(a+1)}]k_{(a+1)} - [1 + \bar{\sigma}_{(a-1)}]k_{(a-1)}$$

Eqn. (6) shows clearly the presence of the various torque harmonics depending on the flux-axis position α; these components can be termed "torque harmonics." From the above definitions it can be seen that each torque-harmonic coefficient is a function of both the ratios β_u/R_u and the flux-harmonic coefficients k_n. When there are no flux harmonics present only the second torque harmonic can exist. When the secondary circuits are symmetrical (i.e. $\beta_1/R_1 = \beta_2/R_2 = \ldots$), several torque harmonics disappear, these depending on the number of secondary phases in the machine.

To test the validity of the theory summarized above, a machine with a so-called 2-phase secondary system was used. This was strictly speaking a four secondary-phase machine, but with only two of its secondary phases in operation. For this machine the torque at synchronous speed is given by

$$T = K_v K_t[sA_0 + dA_2 \cos 2\alpha + sA_4 \cos 4\alpha] \quad . \quad . \quad (7)$$

where $s = (\beta_1/R_1) + (\beta_2/R_2)$, and $d = (\beta_1/R_1) - (\beta_2/R_2)$, and all the torque harmonics of higher order than the 4th have been neglected.

In order to examine conditions at synchronous speed, the Schrage motor was coupled to a synchronous machine wound for the same number of poles, and both machines were connected to the same supply. The circuit diagram is given in Fig. 2, where

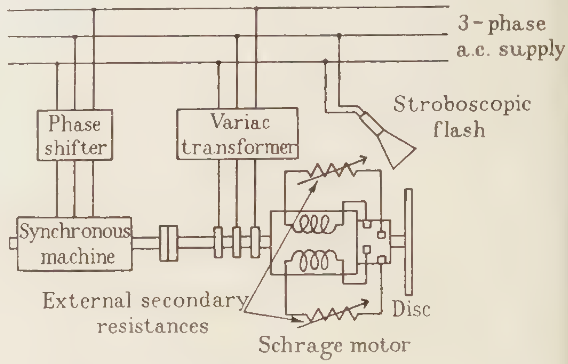

Fig. 2.—Circuit used for testing.

the synchronous machine is shown fed through a phase-shifter, adjustment of which altered the position of the stationary flux in the Schrage motor. The torque in synchronous watts was obtained by measuring the input power to the Schrage motor and subtracting from it the appropriate losses, these being determined by separate tests. The flux-axis position α was obtained by observing a marked disc rotating on the common shaft of the machines, in the light of a strobo-flash.

Typical torque curves are shown in Figs. 3 and 4, where the secondary current (d.c.), is also shown plotted against α (the diagrams show an arbitrary "synchronous position" of the rotor which is a measure of the flux-axis position relative to an arbitrary datum. By "synchronous position" is meant the instantaneous position of the rotor measured in electrical radians at time intervals equal to the periodic time of the mains supply). Fig. 3 shows appreciable secondary asymmetry, obtained artificially by the inclusion of external secondary resistances; the torque relationship can be compared with eqn. (7). Fig. 4 corresponds to the case where the external resistances were adjusted to make d zero, thus balancing the secondaries, and reducing eqn. (7) to

$$T = K_v K_t s[A_0 + A_4 \cos 4\alpha] \quad . \quad . \quad . \quad . \quad (8)$$

A measure of the torque variation can be obtained from the torque curves by taking the ratio $(T_{max} - T_{min})/(T_{max} + T_{min})$. This can be compared with a corresponding ratio, predicted by using either eqn. (7) or (8), for which it is necessary to determine

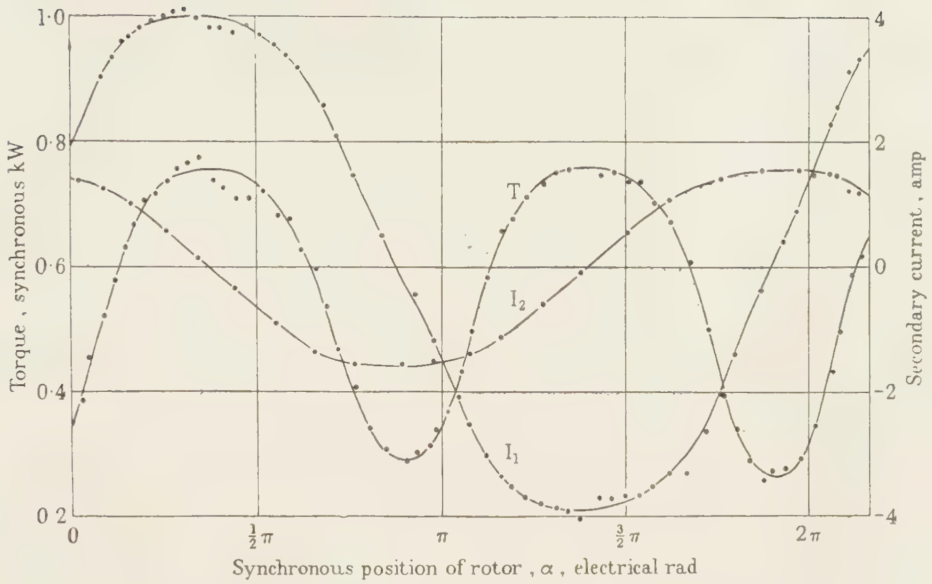

Fig. 3.—Variation of torque and secondary currents with synchronous position.

T = Torque. I_1 = Current in secondary circuit 1.
I_2 = Current in secondary circuit 2.
Applied primary voltage = 250 volts.
Brush spread, β = 1·5 electrical deg.
Ohmic resistance of secondary circuit 1 = 0·286 ohm.
Ohmic resistance of secondary circuit 2 = 0·767 ohm.

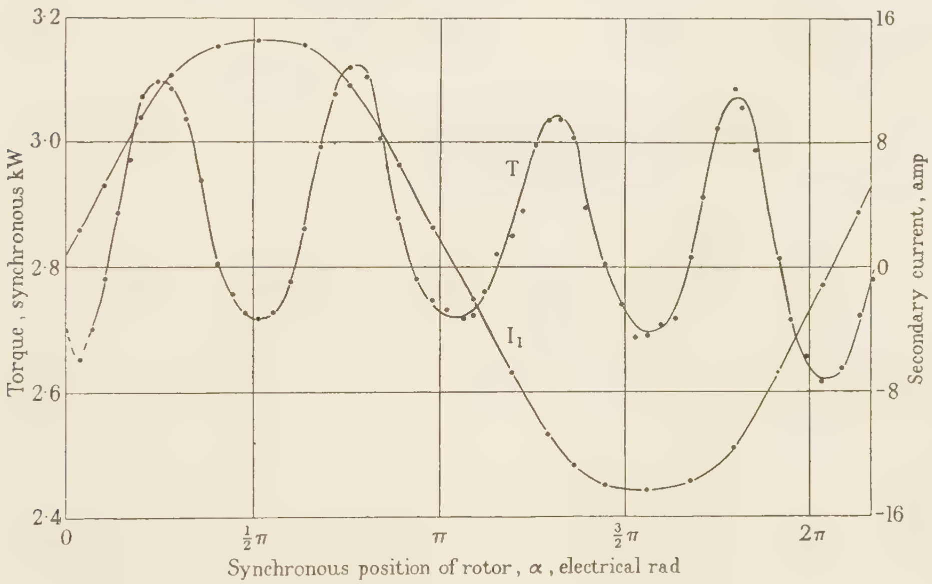

Fig. 4.—Variation of torque and secondary currents with synchronous position.

T = Torque. I_1 = Current in secondary circuit 1.
Applied primary voltage = 220 volts.
Brush spread, β = 30 electrical deg.
Ohmic resistance of secondary circuit 1 = 0·730 ohm.
Ohmic resistance of secondary circuit 2 = 0·714 ohm.

he values of $\bar{\sigma}_3$, $\bar{\sigma}_5$, k_3, k_5 in order to evaluate A_0, A_2 and A_4. The coefficients $\bar{\sigma}_3$ and $\bar{\sigma}_5$ involve only winding data, and can be easily evaluated. Coefficients k_3 and k_5 were obtained under different conditions by plotting the open-circuit brush voltage of one secondary phase (taken at synchronous speed) against the flux-axis position, α, and extracting the relevant space harmonics from the resulting curve by harmonic analysis.

The predicted values of torque variation are given in col. 4 of Table 1. It was, however, necessary to correct these figures because of the effect of non-linear brush-contact resistance present in each secondary circuit. This effect was taken into account by assuming that the secondary-current/α relationship [given by eqn. (3)] contained a third-harmonic component depending entirely on the non-linearity of the d.c. voltage/current charac-

Table 1

Percentage Torque Variations

Condition of secondaries	Primary line voltage	Brush spread β	Percentage torque variation			
			From torque curves	Predicted by syncronous test	Corrected for contact resistance	Predicted by standstill test (not corrected)
	volts	deg	%	%	%	%
Asymmetrical	250	1·5	44·5	45·8	—	45·2
Symmetrical	220	30	2·3	4·6	2·2	4·3
Symmetrical	250	30	6·7	8·1	5·9	6·1
Symmetrical	280	30	8·4	9·4	7·3	7·7
Symmetrical: Min. external resistances ..	250	12	5·3	9·1	4·3	6·7

teristic of each secondary circuit. The corrected figures, given in col. 5, compare favourably with values actually obtained from corresponding torque curves (col. 6).

The Table shows also the amount of torque variation present when the secondaries are made symmetrical, and how the amount depends on the primary line voltage, the rated value of which is 250 volts.

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STEADY-STATE STABILITY OF SYNCHRONOUS GENERATORS AS AFFECTED BY REGULATORS AND GOVERNORS

621.313.322 : 621.3.016.35 Monograph No. 134 S

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(Digest *of a paper published in June*, 1955, *as an* Institution Monograph *and to be republished in Part C of the* Proceedings.)

The operating limit of a synchronous alternator in the leading-power-factor region is determined mainly by the steady-state stability, and this limitation can be modified considerably by automatic control of the alternator field-excitation and the prime-mover torque.

When using fast and continuously acting voltage or power-angle regulators controlling the excitation voltage it is possible to extend the steady-state stability limit, and the new limit is called the "dynamic stability limit." On the other hand, governor action may introduce hunting effects at normal operating conditions and can reduce the stability.

The steady-state and dynamic stability limits depend, not only on the alternator, but also on the load and system characteristics. In general, however, any particular alternator is only a minor component in a large supply system, and as a first approximation the alternator can be considered as being connected to an infinite busbar. Hence, the basis for most stability studies[1–6] is the assumption that the alternator is feeding into a relatively large system which can be represented by an infinite busbar, as shown in Fig. 1.

The determination of the steady-state stability limit for a machine with discontinuous regulation is straightforward, and a mathematical expression for this limit can be deduced directly from the steady-state vector diagram.[1] However, when considering feedback with regulators or governors a more accurate machine analysis is required allowing for field time-constant, inertia and other transient quantities.

Fig. 1.—Synchronous generator connected to an infinite busbar through a reactance X_e.

At the dynamic limit the instability usually shows up as hunting or self-excited oscillations, and the alternator will fall out of synchronism as the oscillations build up. The period of these oscillations depends on the regulator and governor characteristics, and ranges from 0·5 to 10 sec or more for large machines. Thus an alternator cannot be represented simply by its synchronous reactance, as this neglects the faster changes in the variables. On the other hand, representing the machine by its transient reactance is not justified either, since this is also an over-simplification. A more accurate analysis has to be based on the general machine theory as given originally by Park[8] and found in many texts.

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Ordinary servo-mechanism theory can be used to analyse the erformance of the regulator or the governor, and once the omplete system equations, including those for the alternator, re established the stability limits can be found by using standard tability criteria.[7,9]

In the present paper general methods of determining the ynamic stability limit are discussed and the effects of excitation nd prime-move torque control are investigated. In the analysis r design of a control system there are usually many parameters which have to be considered, such as controller gain, regulation, ime delays, etc. The system equations themselves are very omplex, and it has been found that an automatic computer is ractically essential if a detailed investigation is contemplated. For some of the examples analysed in the paper the differential nalyser of the Mathematical Instruments Section, Common-wealth Scientific and Industrial Research Organization, Sydney,[10] as been used.

Machine Equations

The general equations[8] for synchronous machines have found ittle application because of their complexity. For steady-state tability studies, however, these equations can be simplified and inearized, since only small variations in the variables are to be onsidered for any particular load condition.

For example, the output voltage v_t of the alternator is made up f the original steady-state value v_{t0} and a small deviation Δv_t ue to the disturbance that is taking place, i.e.

$$v_t = v_{t0} + \Delta v_t$$

All other machine quantities can be expressed similarly, and the inal equations will be considerably simplified when expressed in erms of the small variations.

The machine equations can be established for the simplest case f the machine feeding into an infinite busbar through a reac-ance X_e. More complex cases can be analysed as well, but the athematics becomes very involved and is not considered here.

Regulators

A regulator compares some machine quantity such as the utput voltage with a reference quantity and controls the field oltage according to the error. The purpose is to reduce any teady-state and transient variations in the controlled variable. A general regulator circuit is shown in Fig. 2, and the effect of

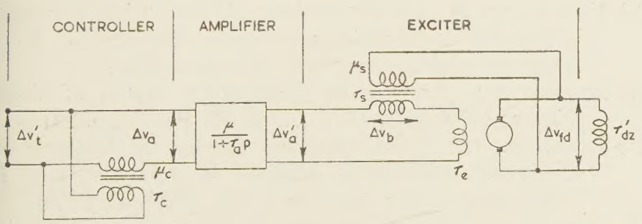

Fig. 2.—A typical regulator circuit.

uch an output voltage regulator is shown in Fig. 3. The perating range is improved throughout the whole leading-power-actor region[5] in the case of a typical 30 MW alternator.

To derive an operating limit as shown in Fig. 3, the stability t a large number of load conditions has to be determined. For ny particular power factor and current the machine is either table or not, and the actual stability limit is found by interpola-ion. The accuracy depends on the spacing of the individual oad conditions considered, and obviously a large number of olutions is required.

The operating limit of Fig. 3 has been derived for one particular

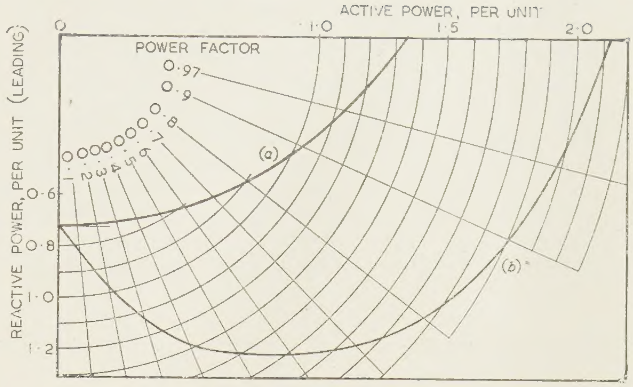

Fig. 3.—Steady-state stability limit of a 30 MW alternator.

(a) With discontinuous regulation.
(b) With continuous regulation.

$H = 6\cdot0$, $D = 3\cdot0$, $v_{t0} = 1\cdot0$
$X_d = X_q = 1\cdot39$, $X'_d = 0\cdot22$, $X_e = 0\cdot4$
Field time-constant, $\tau'_{d0} = 5\cdot9$ sec, $\tau_e = \tau_s = 1\cdot6$ sec.

set of regulator parameters. To determine optimum parameter values a more detailed analysis is necessary. For example, the effect of the feedback-amplifier time-constant τ_a of the regulator shown in Fig. 2 can be derived by means of polar transfer function diagrams as shown in Fig. 4. The effect of varying the feedback amplification μ and stabilization μ_s is shown in Fig. 5, where stable operation is indicated inside the curve given for any particular load current.

Figs. 4 and 5 apply at unity power factor, and the curves will

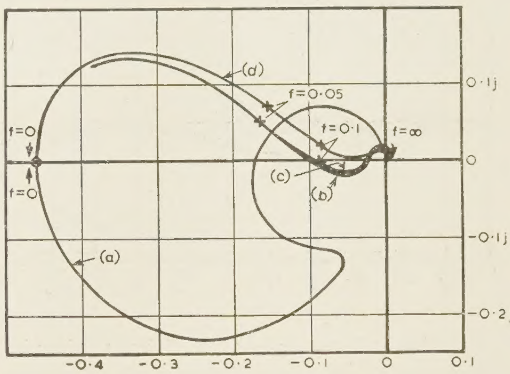

Fig. 4.—Overall transfer functions for voltage-regulated 30 MW machine: $1\cdot0$ p.f., $\mu = 1$, $\mu_s = 3$, $\mu_c = 0$, $0 \leqslant f$ (c/s) $\leqslant \infty$.

(a) $\tau_s = \tau_e = 0$, $\tau_a = 0$.
(b) $\tau_s = \tau_e = 1\cdot6$ sec, $\tau_a = 0$.
(c) $\tau_s = \tau_e = 1\cdot6$ sec, $\tau_a = 0\cdot16$ sec.
(d) $\tau_s = \tau_e = 1\cdot6$ sec, $\tau_a = 0\cdot8$ sec.
Other quantities as for Fig. 3.

change with other power factors. However, optimum controller parameters vary only slightly as the power factor changes, and it is usually sufficient to analyse conditions at one power factor only.

The instability with regulators is caused by various factors. If the regulator operates with no time delay, and if the alternator field time-constant is neglected, there is theoretically no power limit on the machine. If the field time-constant is allowed for, it is found that fast response need not provide maximum stability. As shown in Fig. 6, the optimum response can be found only by a detailed analysis. If the response is too fast it will aid the natural mechanical vibrations[12] of the alternator, which are of the order of 1 c/s, and resonance causes instability.

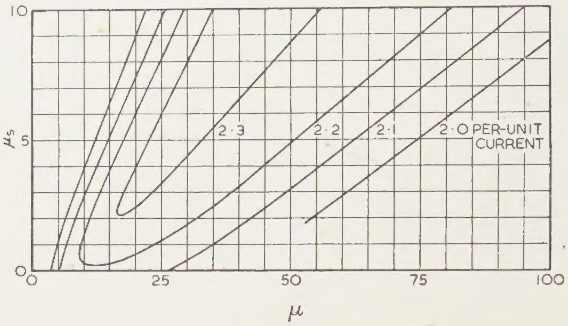

Fig. 5.—Voltage regulator stability contour diagram for unity power factor and $\tau_s = \tau_e = 1 \cdot 6$ sec, $\tau_a = \mu_c = 0$.
Other quantities as for Fig. 3.

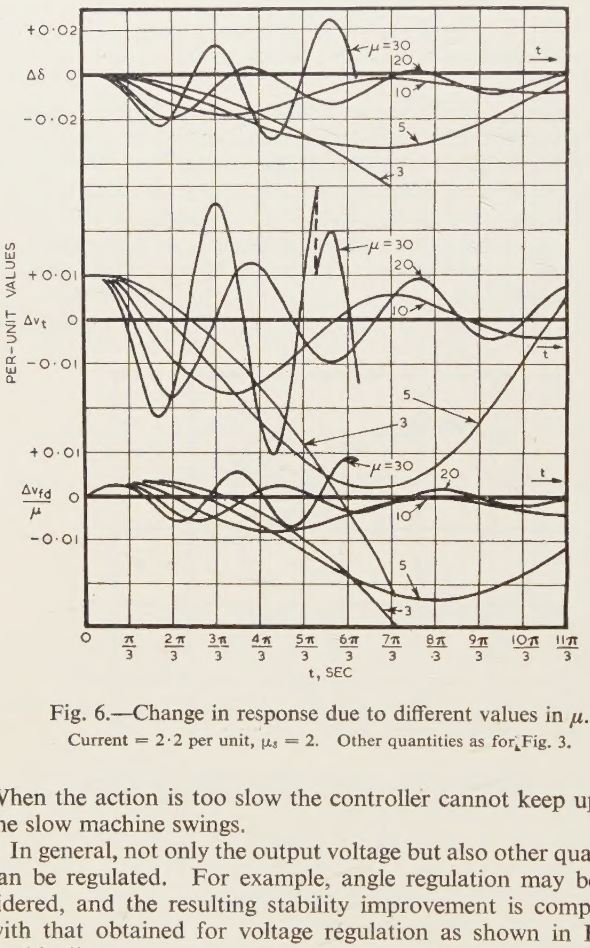

Fig. 6.—Change in response due to different values in μ.
Current = 2·2 per unit, μ_s = 2. Other quantities as for Fig. 3.

When the action is too slow the controller cannot keep up with the slow machine swings.

In general, not only the output voltage but also other quantities can be regulated. For example, angle regulation may be considered, and the resulting stability improvement is comparable with that obtained for voltage regulation as shown in Fig. 7. In this diagram a represents the gain in the regulator amplifier stage.

Governors control the prime-mover output and affect the electrical quantities by shifting the torque angle. The speed of response depends to a large extent on the governor time-constants and also on the inertia of the machines. The natural period of mechanical machine vibrations is very critical when considering the response time of governor mechanisms, since instability can arise if the overall time delay in a governor is of the same order as this period. If possible, the response should be faster, in which case the governors will help in damping out transients.

Often additional prime-mover torque controls are used. The normal tie-line power and frequency controllers[13] have little effect

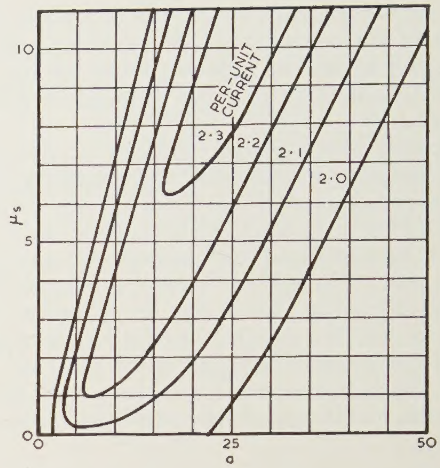

Fig. 7.—Power-angle regulator stability contour diagram for unity power factor and all other quantities as for Fig. 5.

on the stability limit because of their relatively slow rate of response. A detailed analysis of this type of control is again rather tedious if carried out manually, and it has been found in general that stability studies have to be handled on automatic computers.

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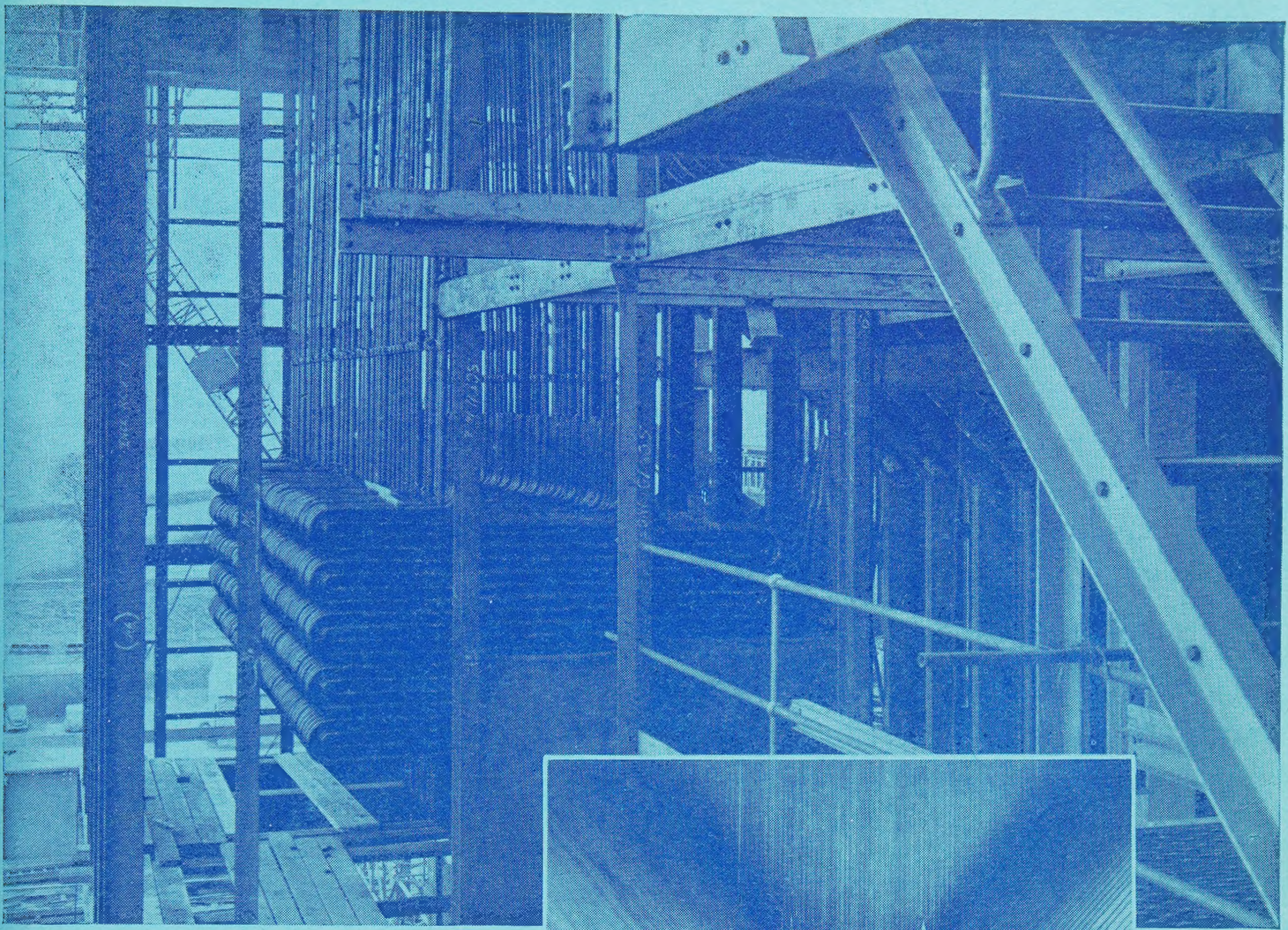
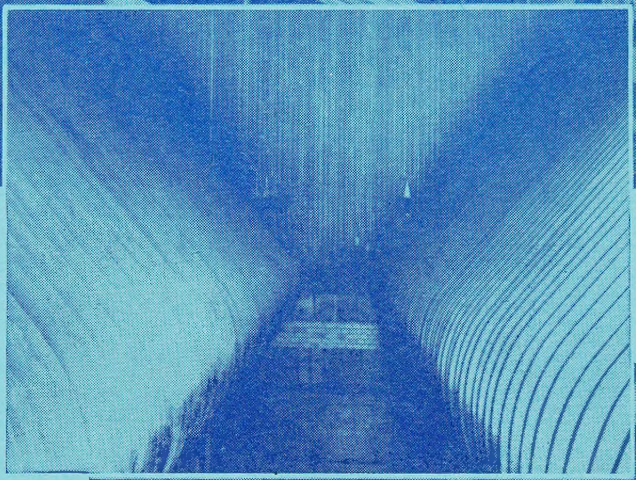
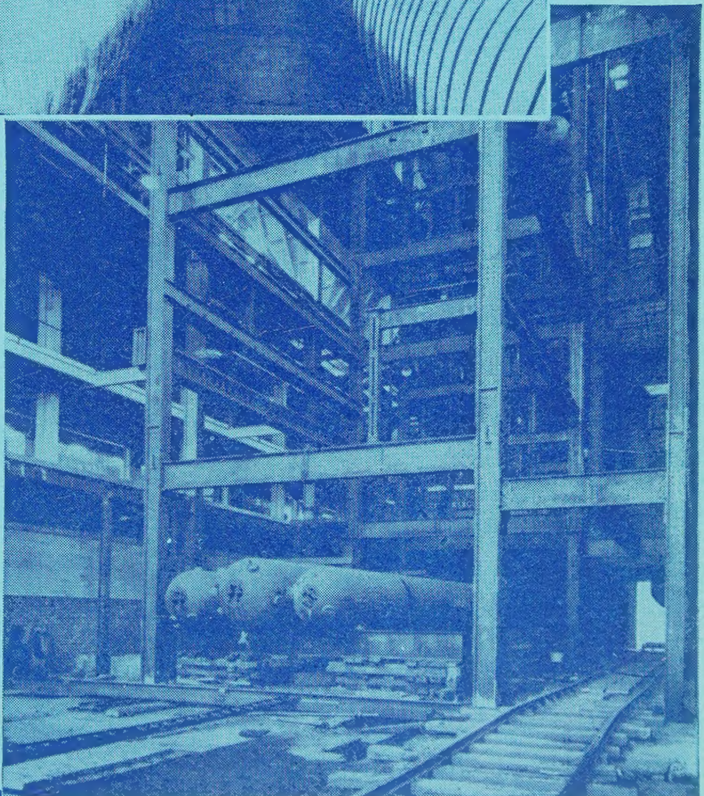




Views of typical boiler installations.



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